x86 and PC architecture

PC architecture
x86 instruction set
gcc calling convention

Abhilash Jindal

Reference. xv6 book: Appendix A

Agenda

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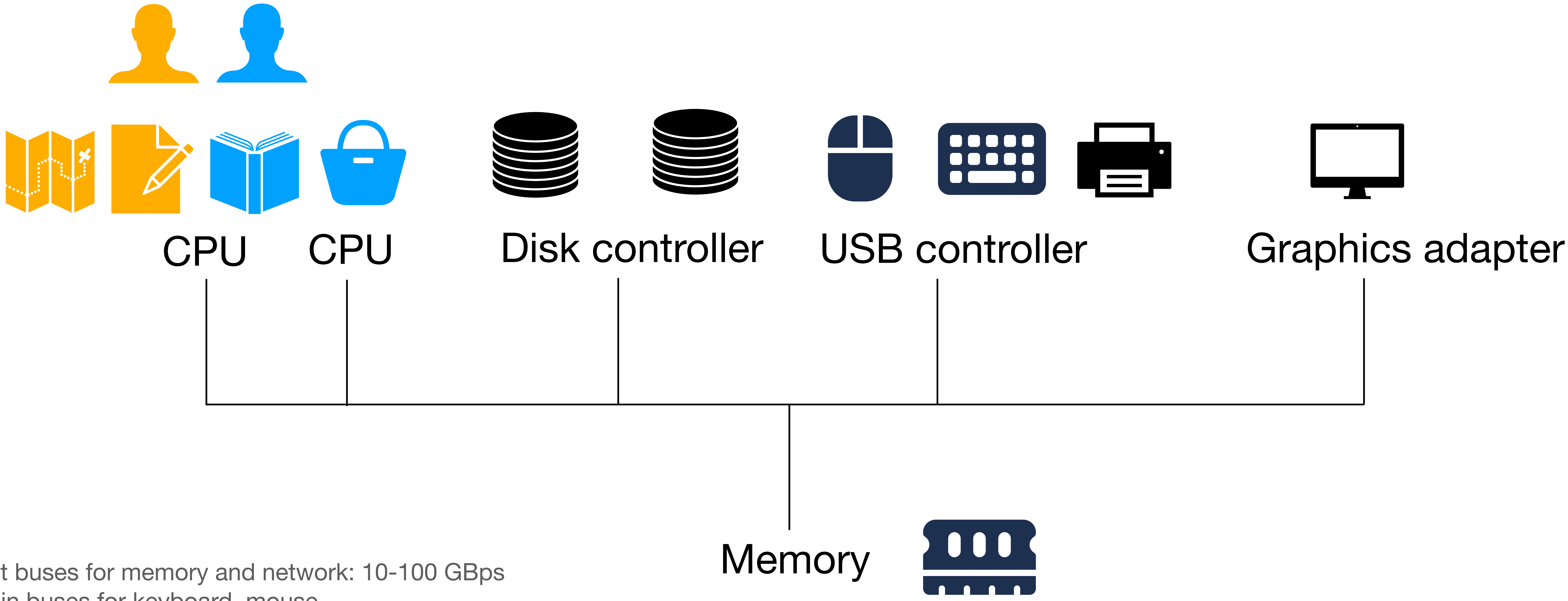
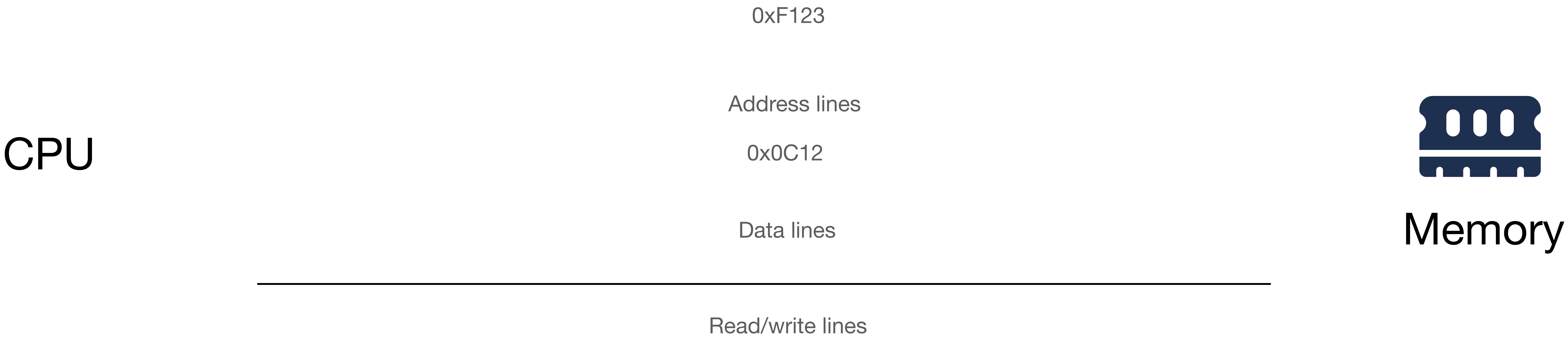
  - Assembly programs are sometimes required by OS to get fine-grained control of the hardware
- Understand gcc calling convention so that we can call C programs from assembly and vice-versa

Computer organization



Fat buses for memory and network: 10-100 GBps
Thin buses for keyboard, mouse

CPU-memory interaction



0xF123

Address lines

CPU

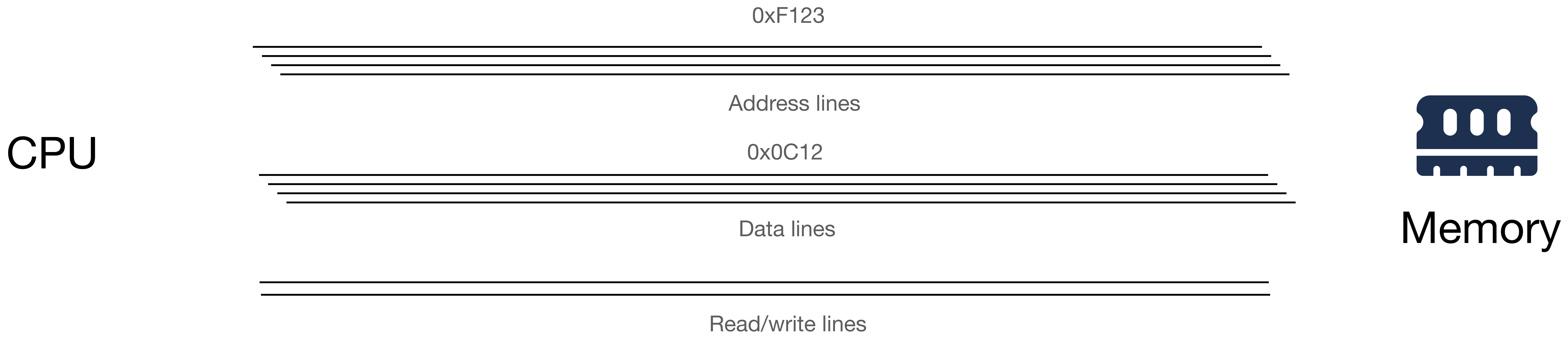
0x0C12

Data lines

Memory

Read/write lines

CPU-memory interaction



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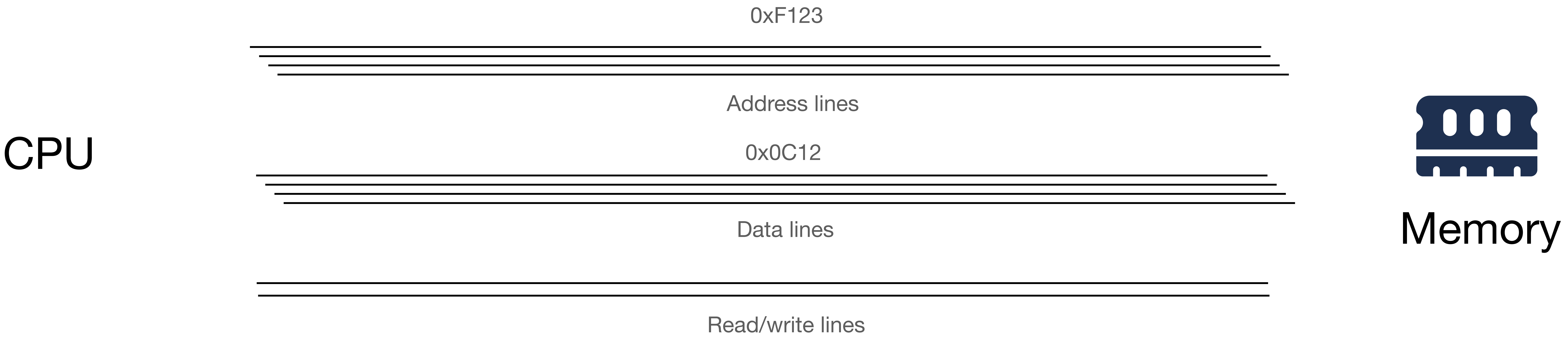

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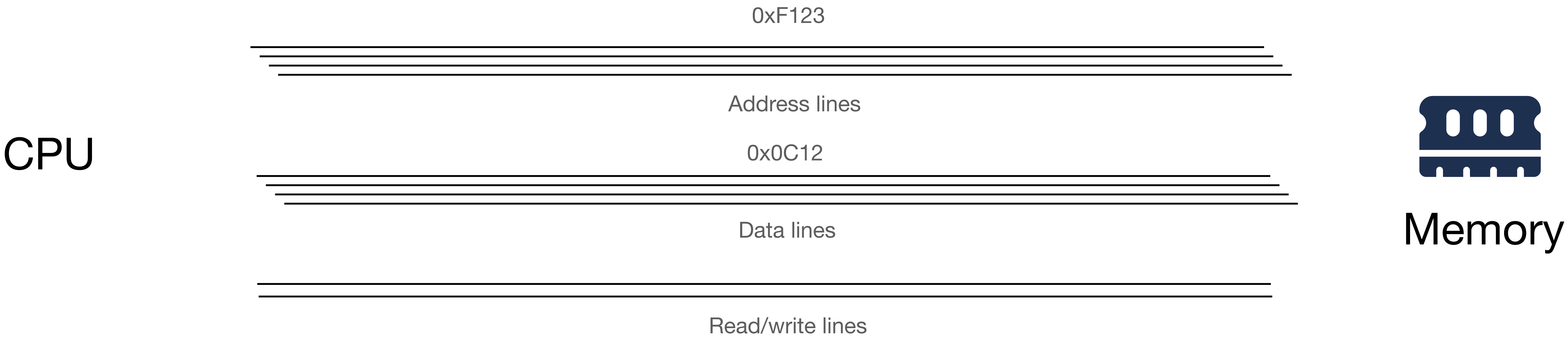

0xF123

Address lines

CPU

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Memory

Read/write lines

- Each read/write takes ~100 cycles
- Faster memory: on-chip registers ~1 cycle.

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- **General purpose registers.**
    - **%eax, %ebx, %ecx, %edx**
    - ***%edi*: destination index, *%esi*: source index**

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mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent

mov instructions

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movl %eax, %edx	edx = eax

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movl %eax, %edx	edx = eax
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movl %eax, %edx	edx = eax
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movl 4(%ebx), %edx	edx=*(int32_t*)(ebx+4)

mov instructions

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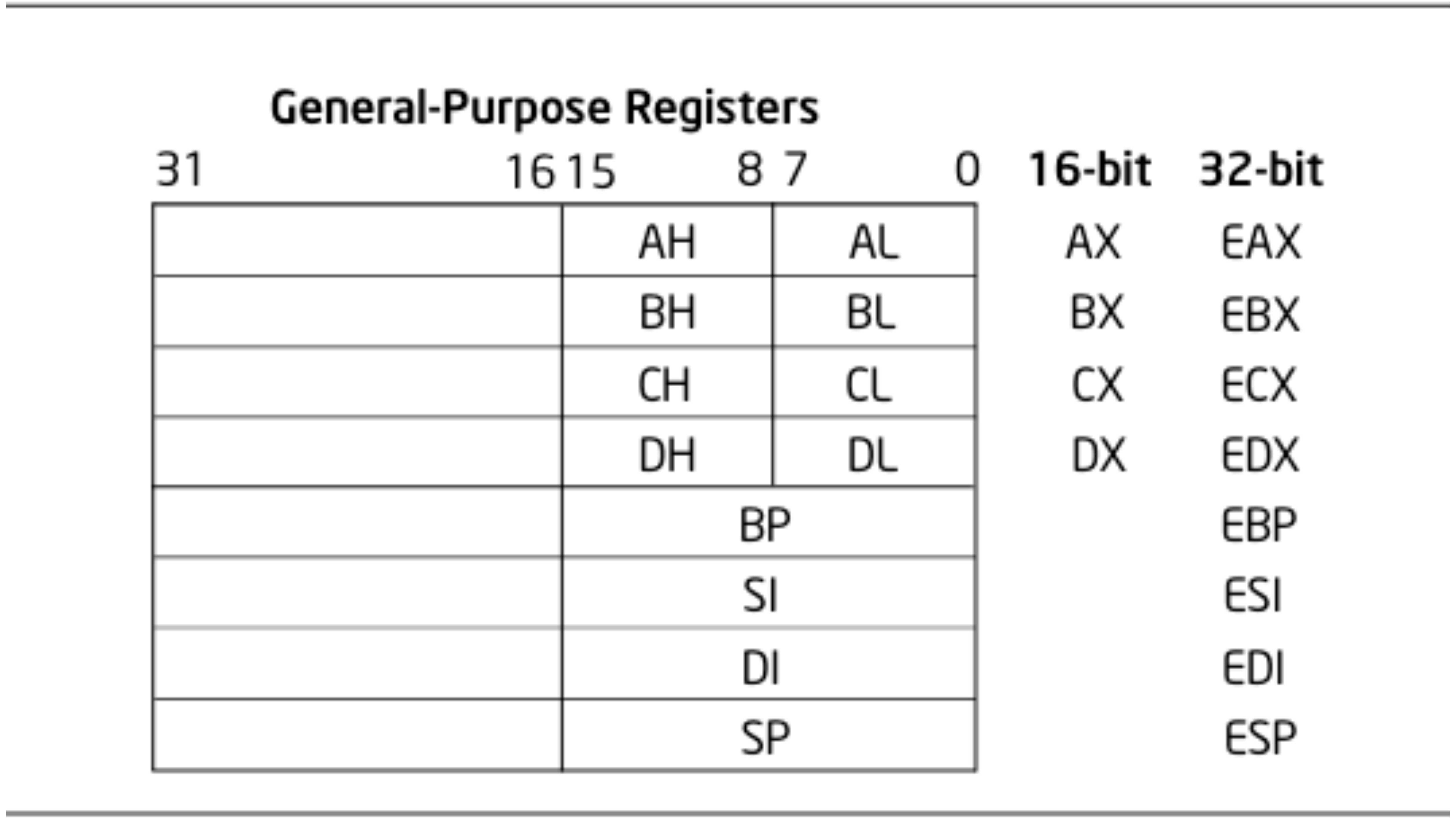
movl 4(%ebx), %edx	edx=*(int32_t*)(ebx+4)

Assembly	"C" equivalent
movsb	*edi = *esi; edi++; esi++;

Other instruction variants



General-Purpose Registers

31 16	15 8	7 0	16-bit	32-bit
	AH	AL	AX	EAX
	BH	BL	BX	EBX
	CH	CL	CX	ECX
	DH	DL	DX	EDX
	BP			EBP
	SI			ESI
	DI			EDI
	SP			ESP

Figure 3-5. Alternate General-Purpose Register Names

Other instruction variants

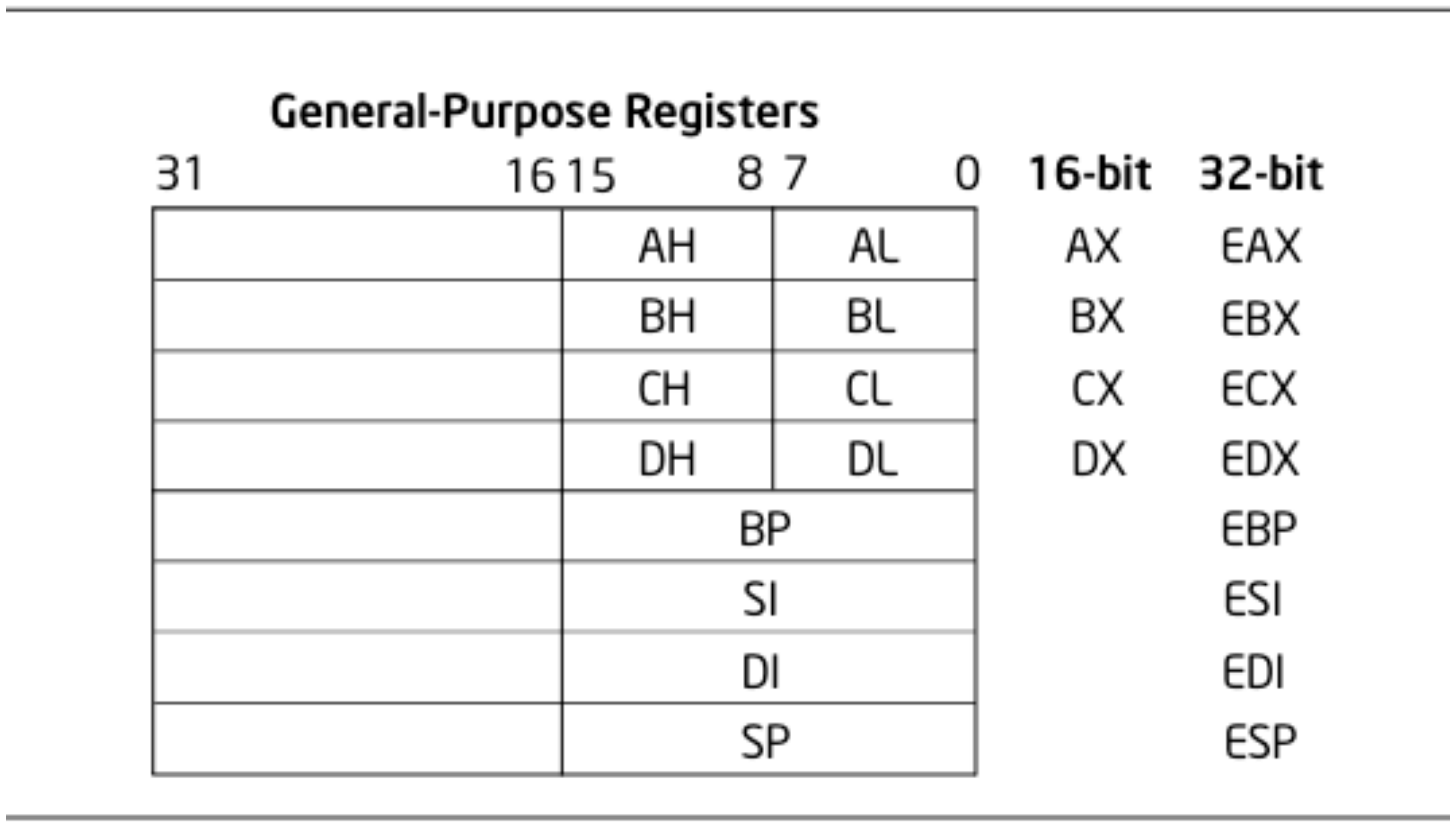


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Figure 3-5. Alternate General-Purpose Register Names

- movw: moves 2 bytes (%ax)
- movb: moves 1 byte (%al, %ah)

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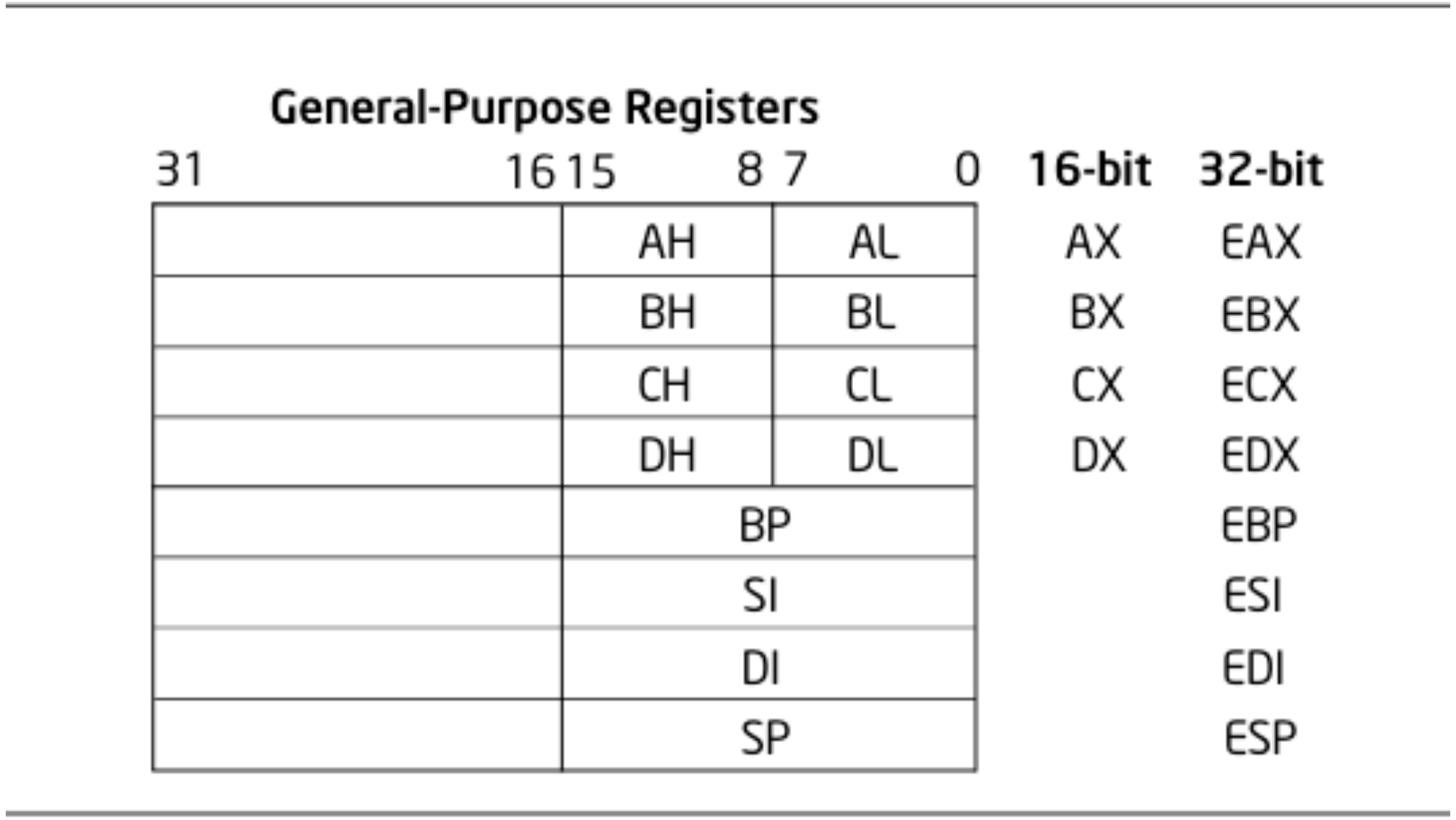

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Figure 3-5. Alternate General-Purpose Register Names

- movw: moves 2 bytes (%ax)
- movb: moves 1 byte (%al, %ah)

Many other instructions: ADD, SUB, MUL, DIV, …

Registers

- General purpose registers.
    - %eax, %ebx, %ecx, %edx
    - *%edi*: destination index, *%esi*: source index
- **Flags register. %eflags**
- Instruction pointer. %eip
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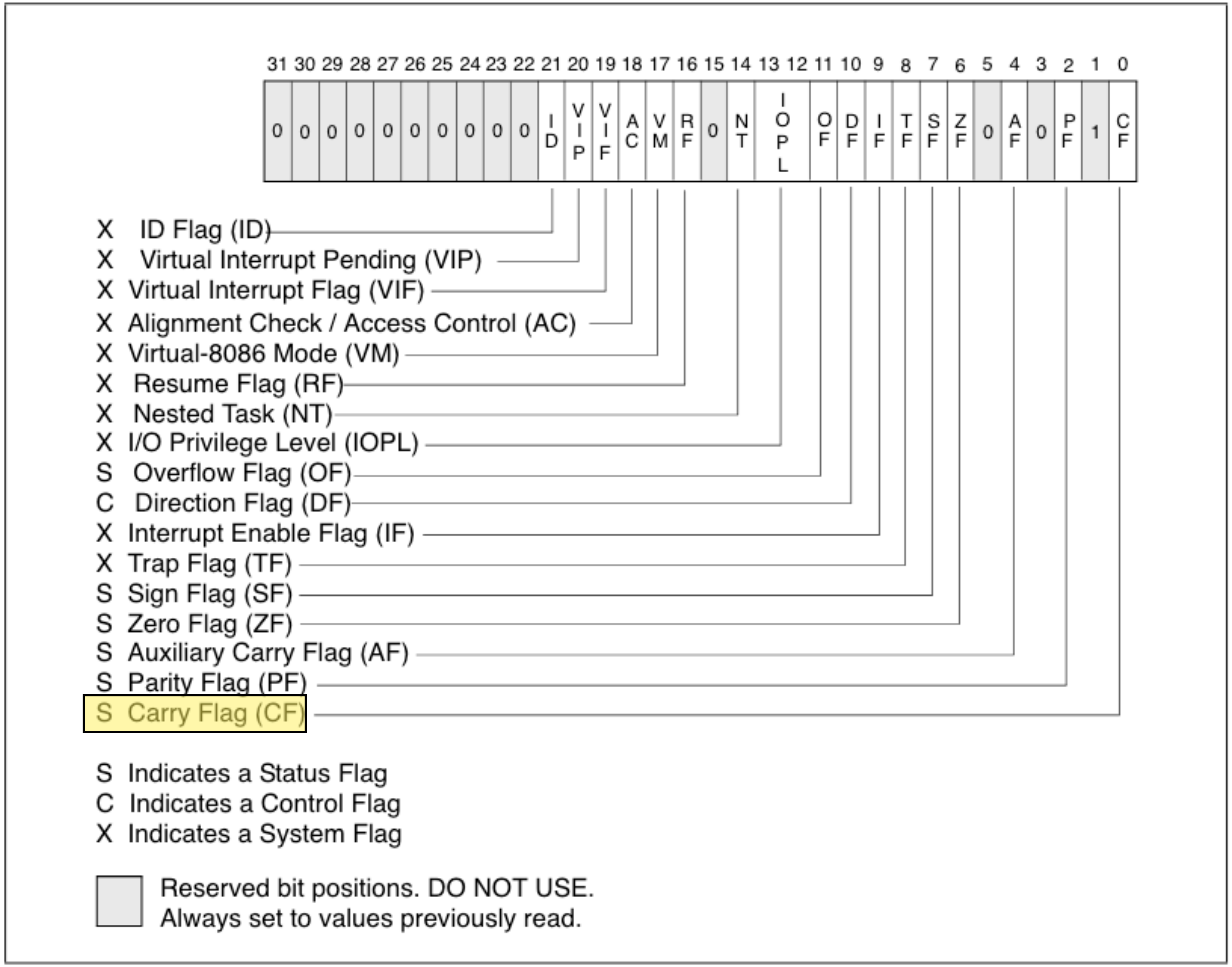
EFLAGS

- Carry flag: Most significant bit overflowed.

```
movl $FFFFFFFF %eax
addl %eax, %eax
```



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	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)
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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)
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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.

Figure 3-8. EFLAGS Register

EFLAGS (2)

- Zero flag: Set if result is zero.

```
xorl %eax, %eax
```

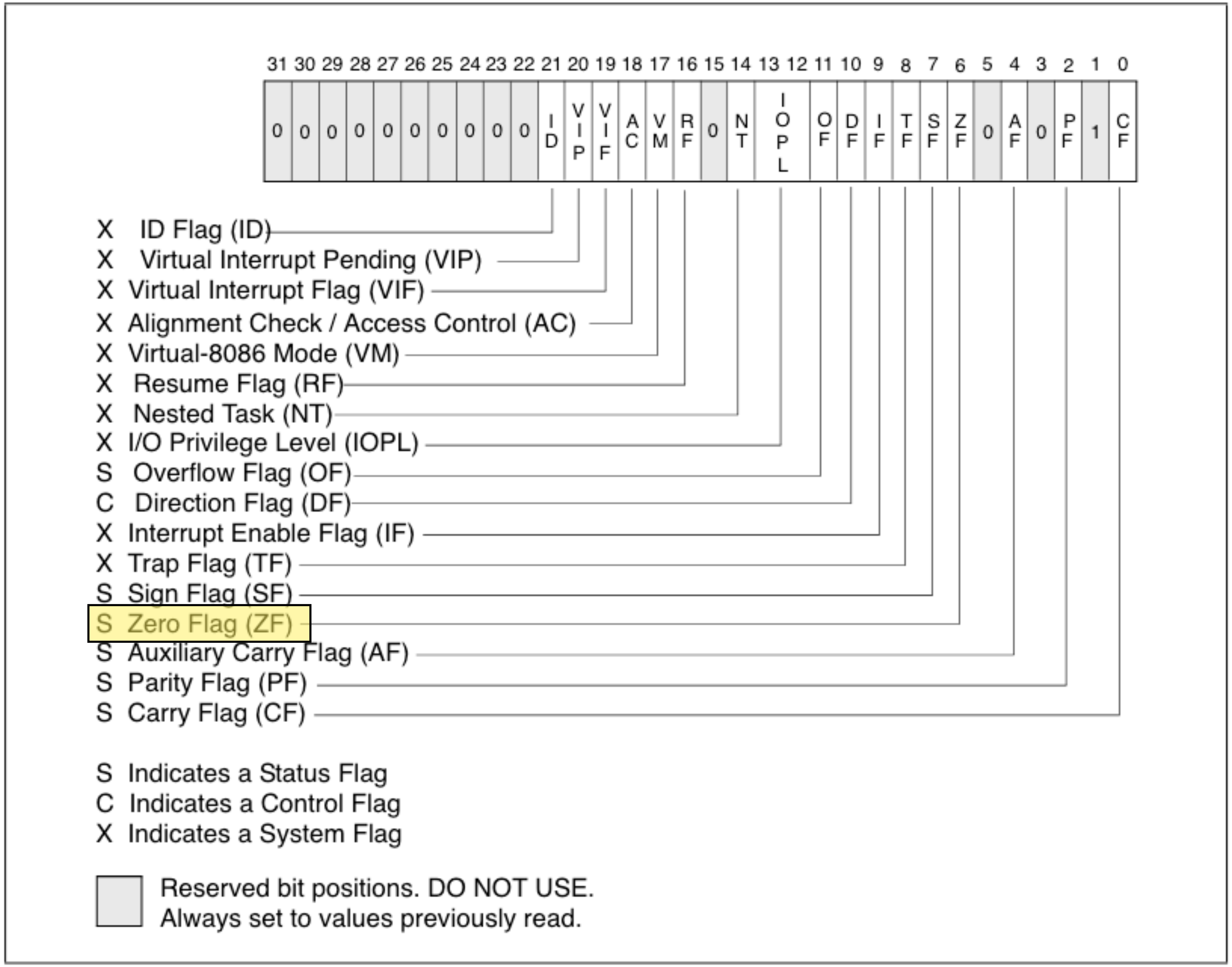
31 30 29 28 27 26 25 24 23 22 21 20 19 18 17 16 15 14 13 12 11 10 9 8 7 6 5 4 3 2 1 0
0 0 0 0 0 0 0 0 0 0 ID VIP VIF AC VM RF 0 NT IOPL OF DF IF TF SF ZF 0 AF 0 PF 1 CF
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Figure 3-8. EFLAGS Register

EFLAGS (3)

- Sign flag: Equal to the most significant bit of the result (which is the sign bit of a signed integer)

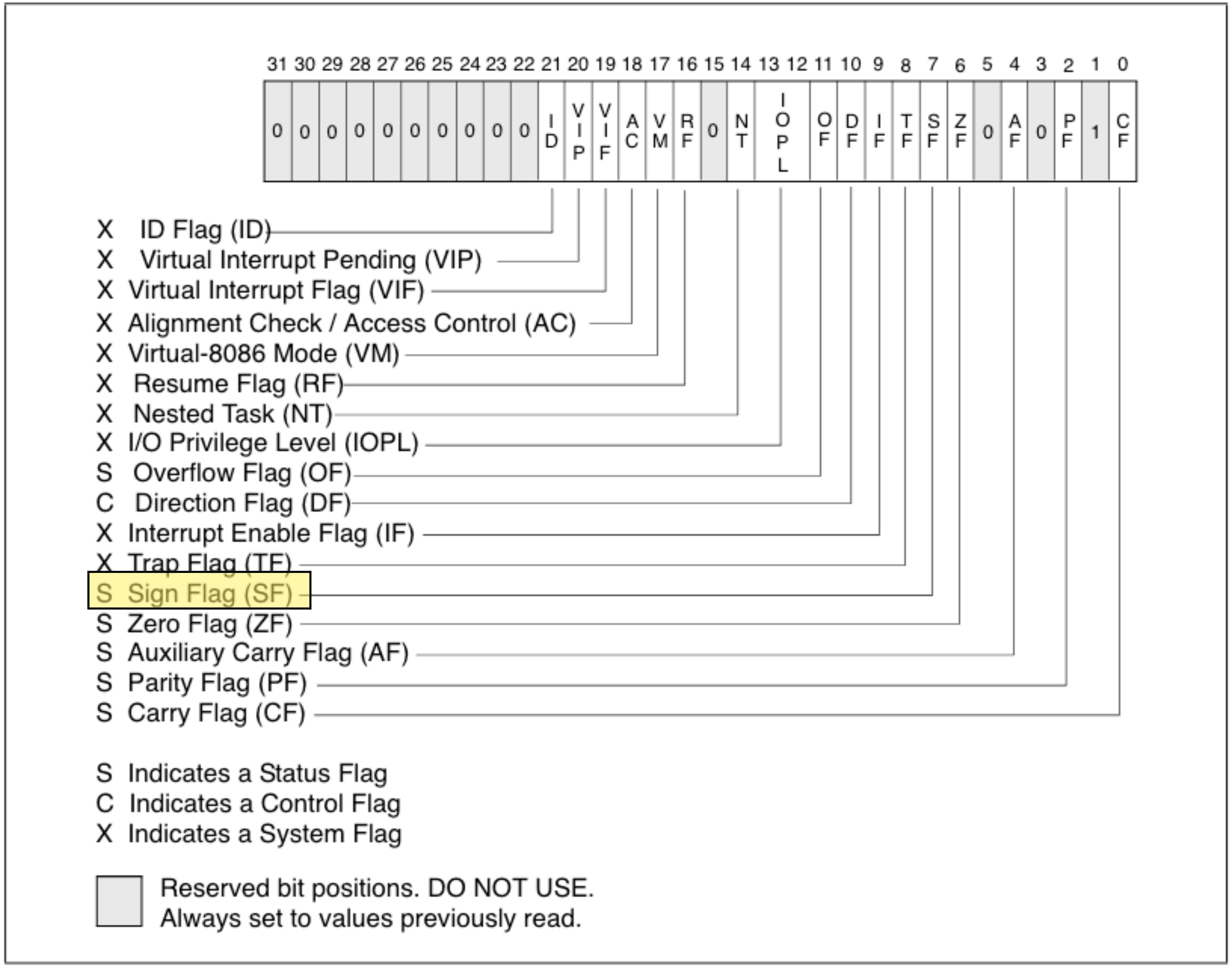

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Figure 3-8. EFLAGS Register

Registers in action

02.flags.c

```
int foo(int x, int y) {
  int z = x + y;
  if(z % 2 == 0)
    return x;
  return y;
}
```

```
gcc -m32 -S -O1 02.flags.c
```

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```

02.flags.s

```
foo:
  movl  4(%esp), %eax      # eax = x
  movl  %eax, %edx        # edx = eax (z = x)
  addl  8(%esp), %edx     # edx += y
  andl  $1, %edx          # edx = (edx & 1). ZF if edx is even.
  cmovne  8(%esp), %eax   # eax = y if !ZF
  ret
```

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  - CALL 0x1234: Similar to JMP, additionally saves the current instruction pointer on stack e.g., function call
  - RET: returns back to callee. Changes %eip to address in stack

Registers in action (2)

02.eip.c

```
int exponent(int x, int y) {
  int z = x;
  while(y > 0) {
    z = z * x;
    y --;
  }
  return z;
}
```

```
gcc -m32 -S -O1 02.eip.c
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Registers in action (2)

02.eip.c

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  while(y > 0) {
    z = z * x;
    y --;
  }
  return z;
}
```

```
gcc -m32 -S -O1 02.eip.c
```

```
exponent:
  movl  4(%esp), %ecx       # ecx = x
  movl  8(%esp), %eax       # eax = y
  movl  %ecx, %edx          # edx = ecx (z = x)
  testl %eax, %eax          # bitwise and eax with eax.
                            # SF if eax<0. ZF if eax=0.
  jle .L1                    # Jump if SF or ZF (y <= 0)
.L3:
  imull %ecx, %edx          # z = z*x
  subl  $1, %eax            # eax-- (y--). ZF if eax=0 (y=0)
  jne .L3                    # Jump back to loop if !ZF
.L1:
  movl  %edx, %eax          # eax = edx (return z)
  ret
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Registers

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Stack pointers

- Stack grows downwards
- %ebp points to return address
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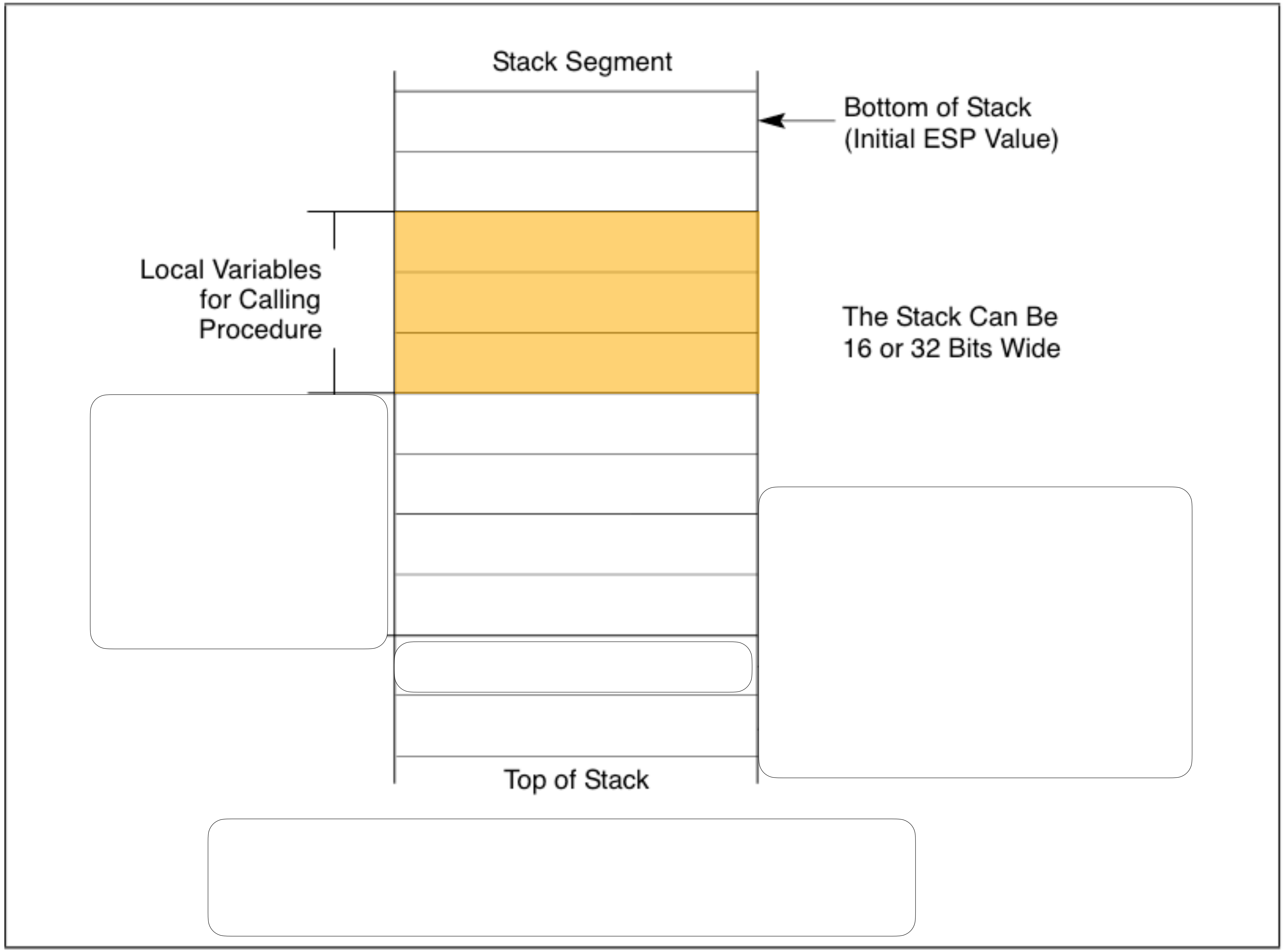

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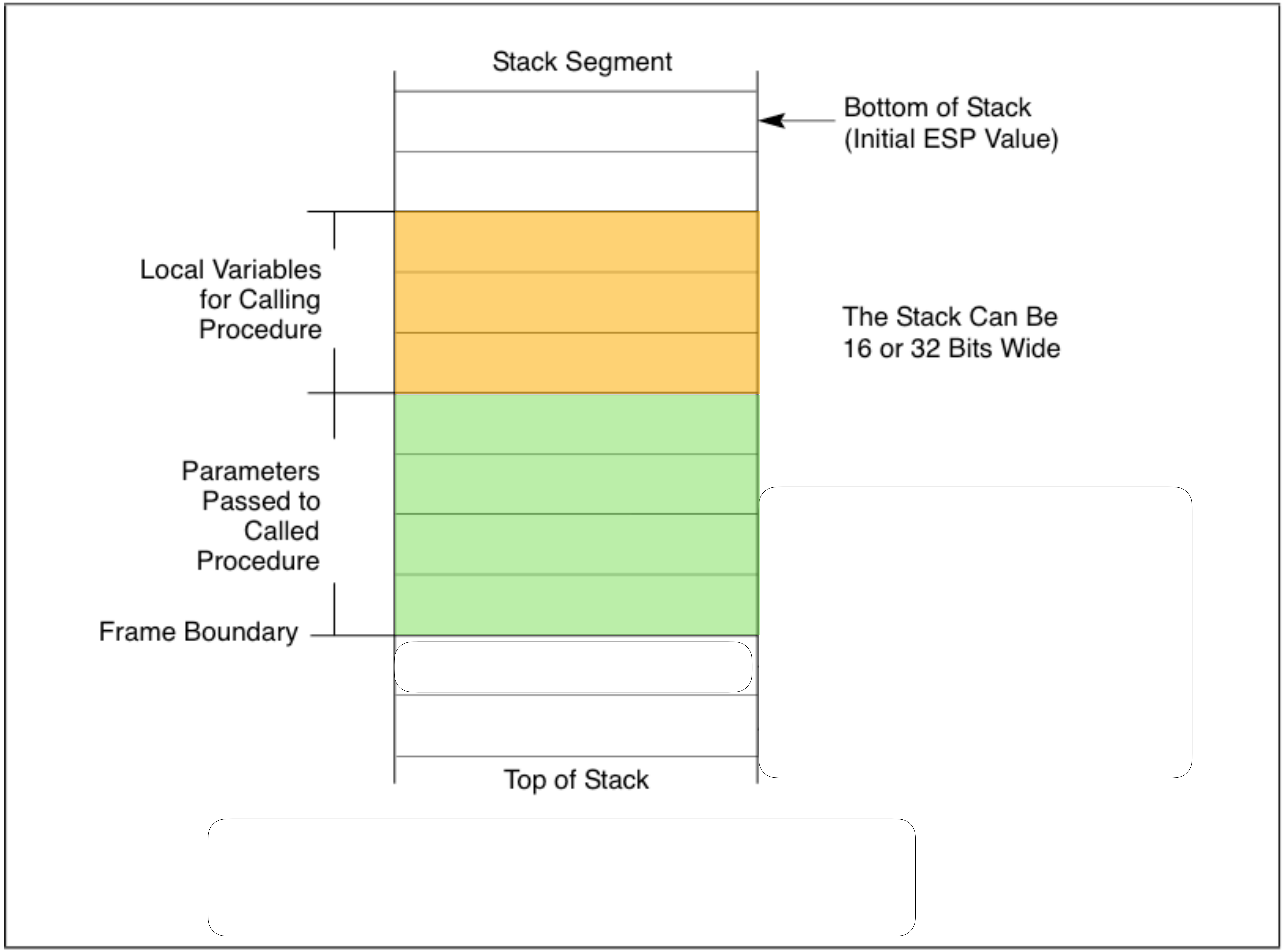

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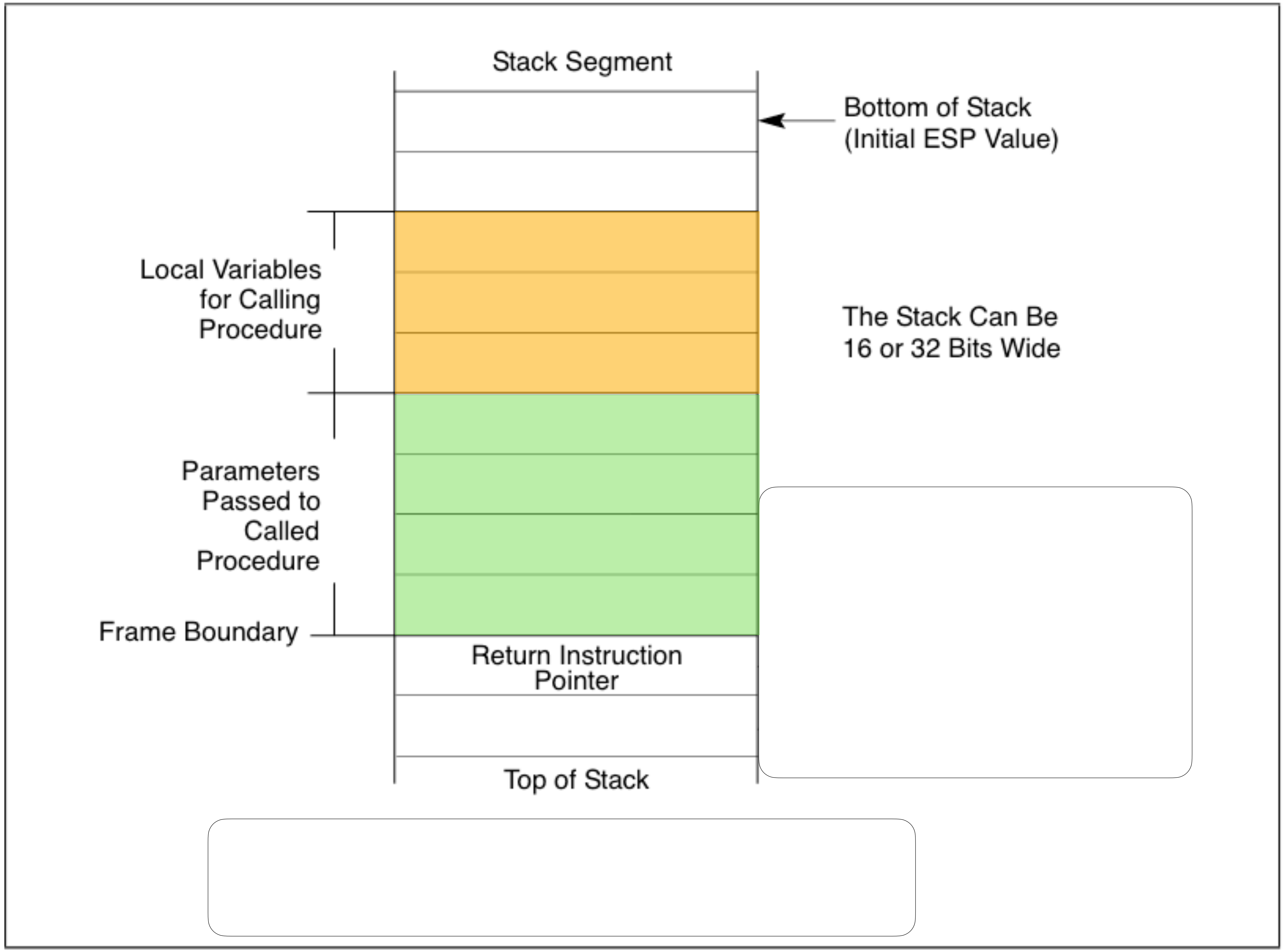
Stack Segment
Bottom of Stack (Initial ESP Value)
Local Variables for Calling Procedure
The Stack Can Be 16 or 32 Bits Wide
Parameters Passed to Called Procedure
Frame Boundary
Return Instruction Pointer
Top of Stack

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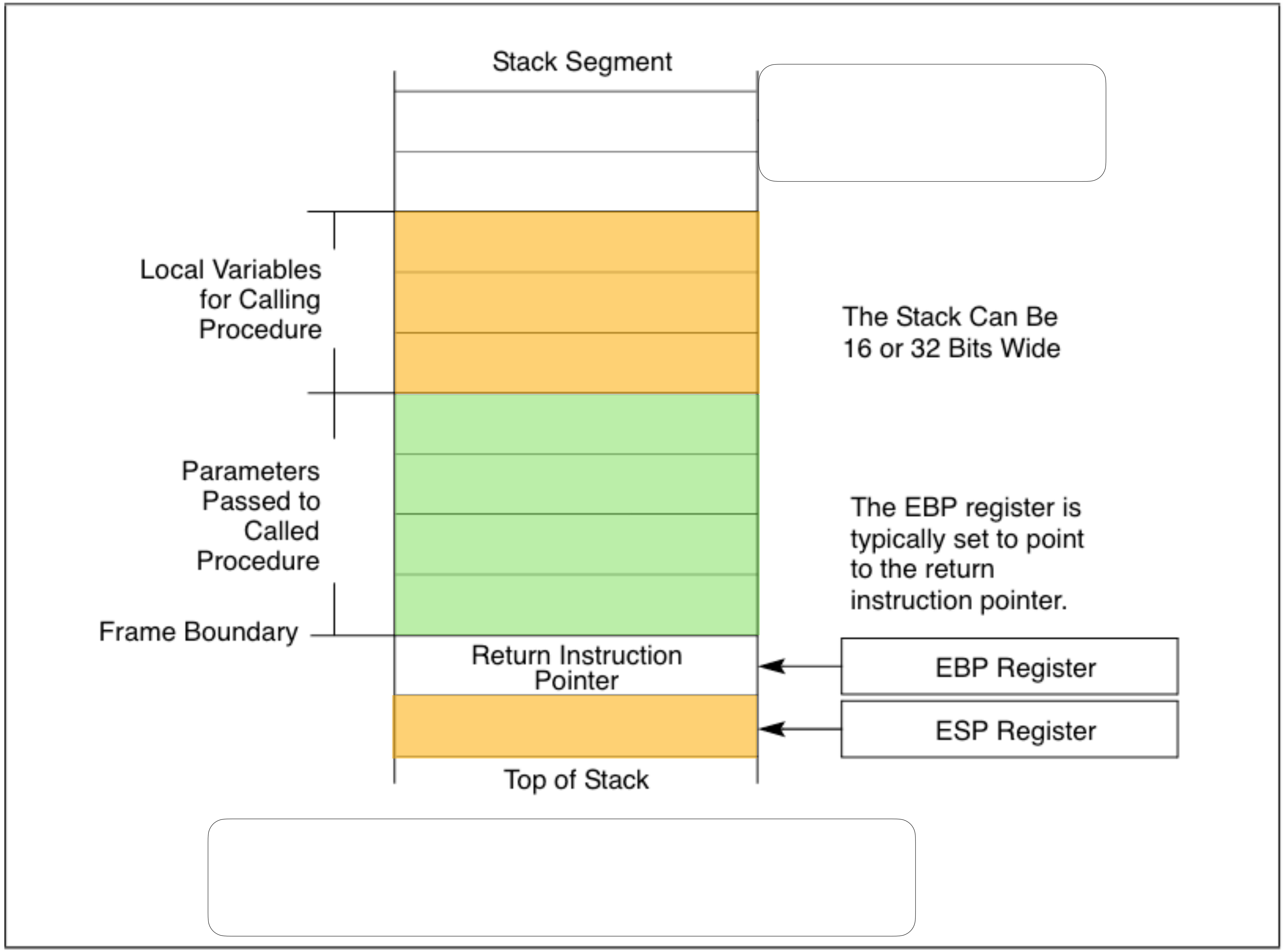
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The EBP register is typically set to point to the return instruction pointer.
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Return Instruction Pointer
EBP Register
ESP Register
Top of Stack

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Stack pointers

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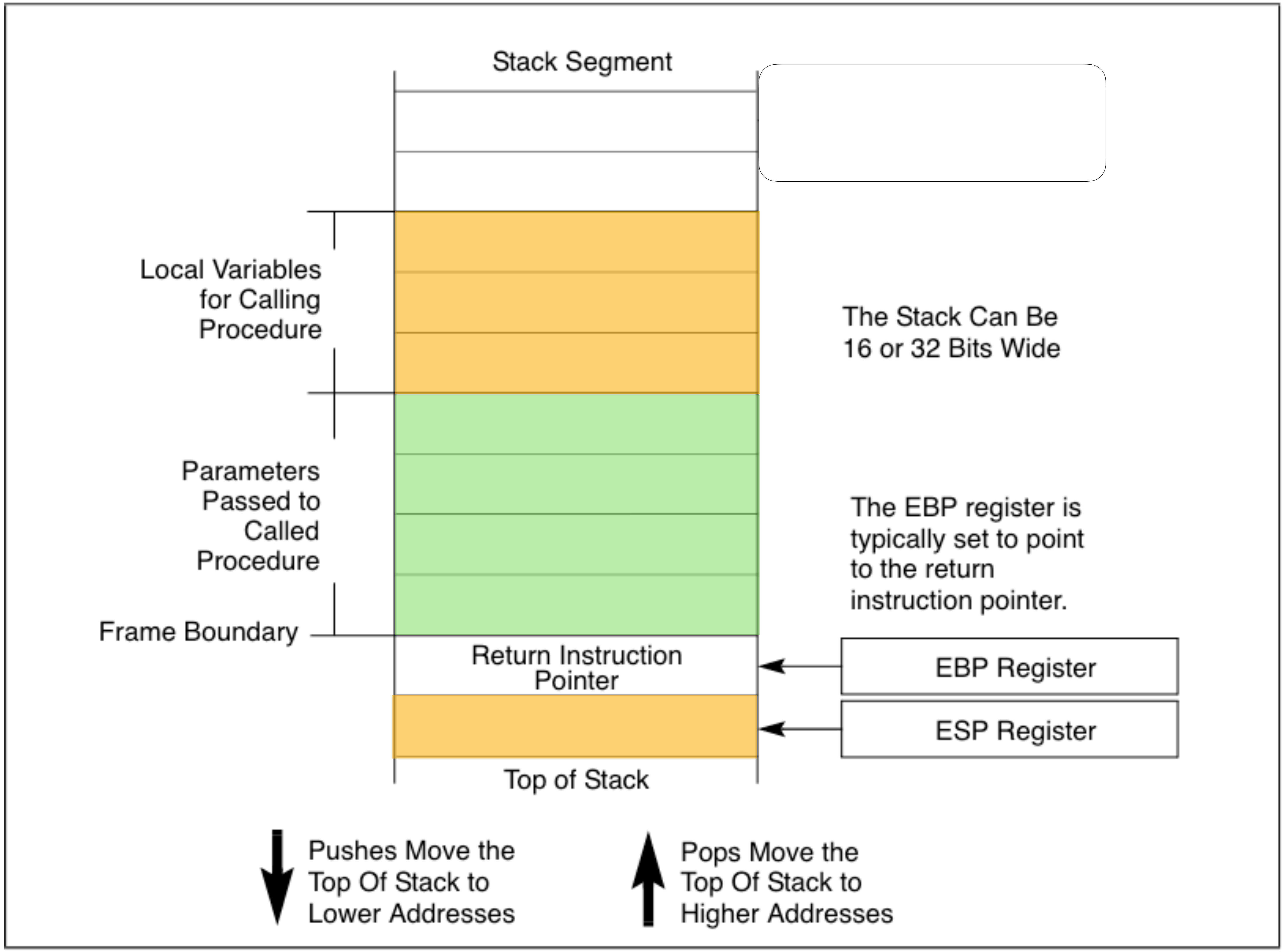
pushl %eax	subl $4, %esp movl %eax, (%esp)
popl %eax	movl (%esp), %eax addl $4, %esp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Frame Boundary
Return Instruction Pointer
EBP Register
ESP Register
Top of Stack
Pushes Move the Top Of Stack to Lower Addresses
Pops Move the Top Of Stack to Higher Addresses

Figure 6-1. Stack Structure

Calling a function

main -> foo(x, y) -> bar(z)

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- bar reads z from the stack into registers, does computation on them
- Executes RET instruction to jump %eip to return address in the function foo

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- foo reads parameters from the stack into registers, does computation on them
- foo pushes bar’s parameters (z) on the stack, executes CALL instruction
- bar reads z from the stack into registers, does computation on them
- Executes RET instruction to jump %eip to return address in the function foo
- foo executes RET instruction

Function calling in action

```
02.c

int foo(int x, int y) {
  return x + y;
}

int main() {
  return foo(41, 42);
}
```

gcc -m32 -S 02.c →

pushl %eax	subl $4, %esp movl %eax, (%esp)
popl %eax	movl %eax, (%esp) addl $4, %esp

```
02.s

_foo:
  pushl %ebp                # Save caller's base pointer
  movl  %esp, %ebp          # ebp = esp
  movl  8(%ebp), %eax       # eax = *(ebp + 8)
  addl  12(%ebp), %eax      # eax = eax + *(ebp + 12)
  popl  %ebp                # Restore caller's base pointer
  retl                      # change eip to return address

  .globl  _main                           ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                # Save caller's base pointer
  movl  %esp, %ebp          # ebp = esp
  subl  $24, %esp           # esp = esp - 24
  movl  $0, -4(%ebp)        # *(ebp-4) = 0
  movl  $41, (%esp)         # *(esp) = 41
  movl  $42, 4(%esp)        # *(esp+4) = 42
  calll _foo                # Push current eip on to stack, jump to foo
  addl  $24, %esp           # esp = esp + 24 (Restore caller's esp)
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```

Function calling in action: Stack

eip

```
02.s

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  pushl %ebp                     Save caller’s base pointer
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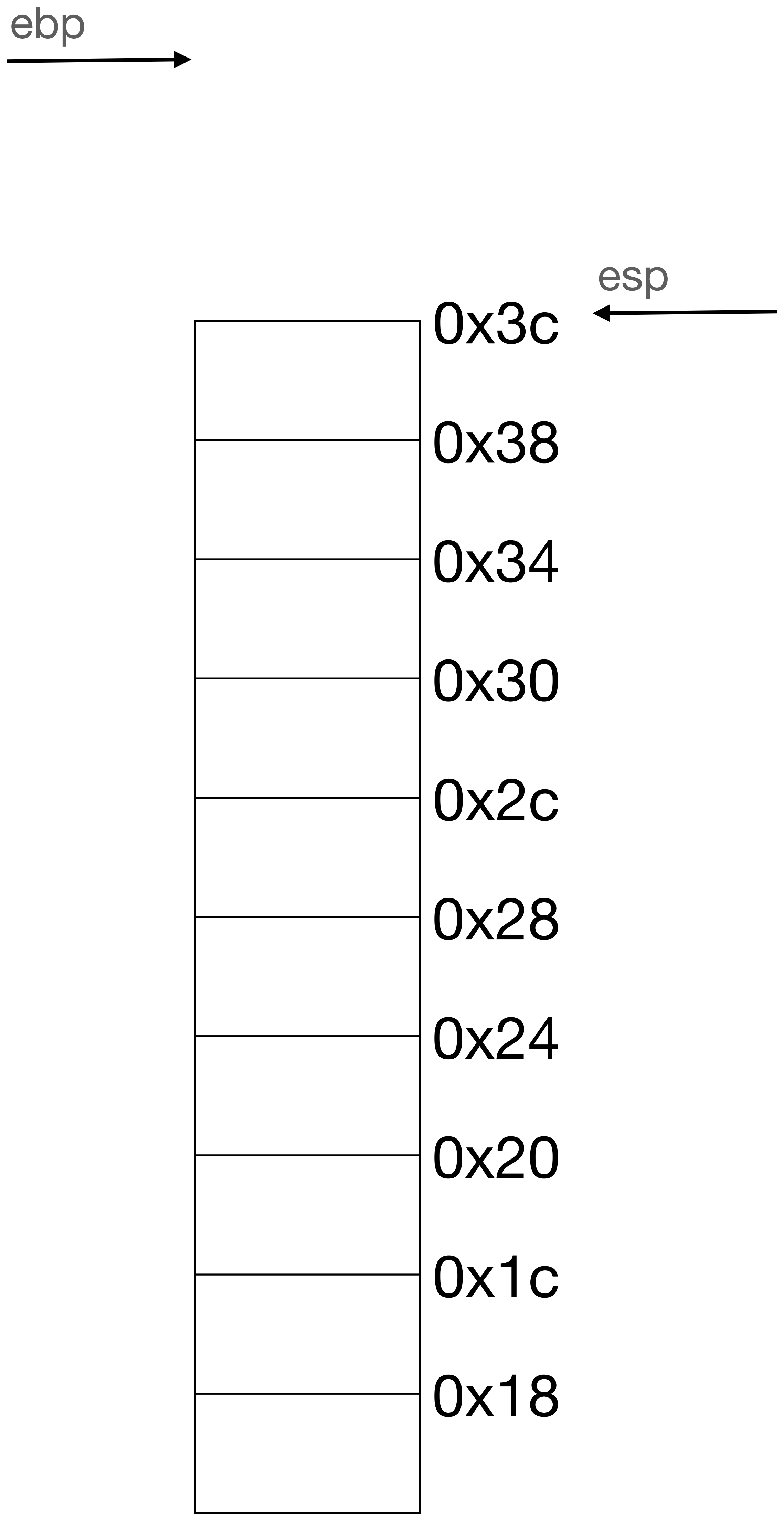

Function calling in action: Stack

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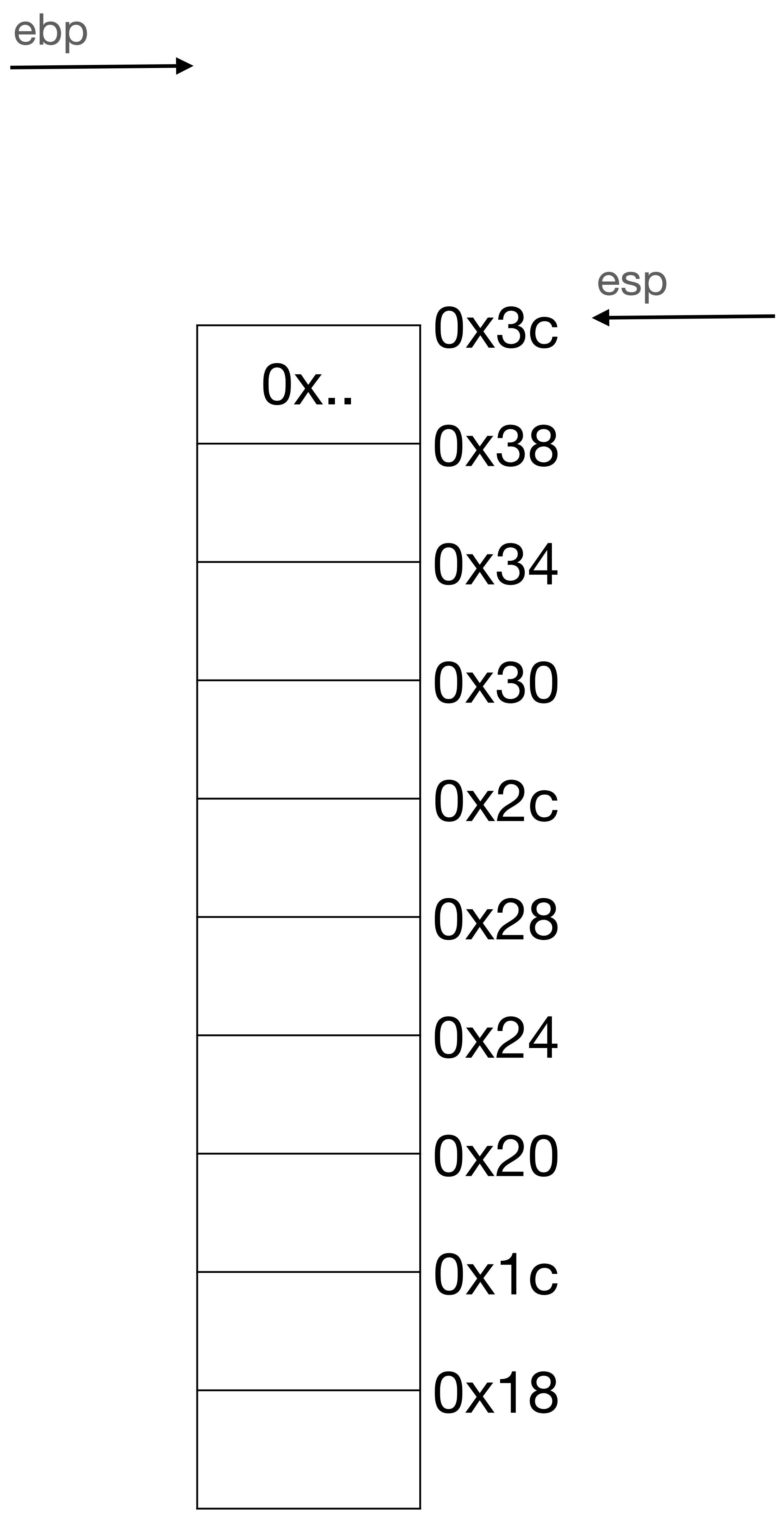
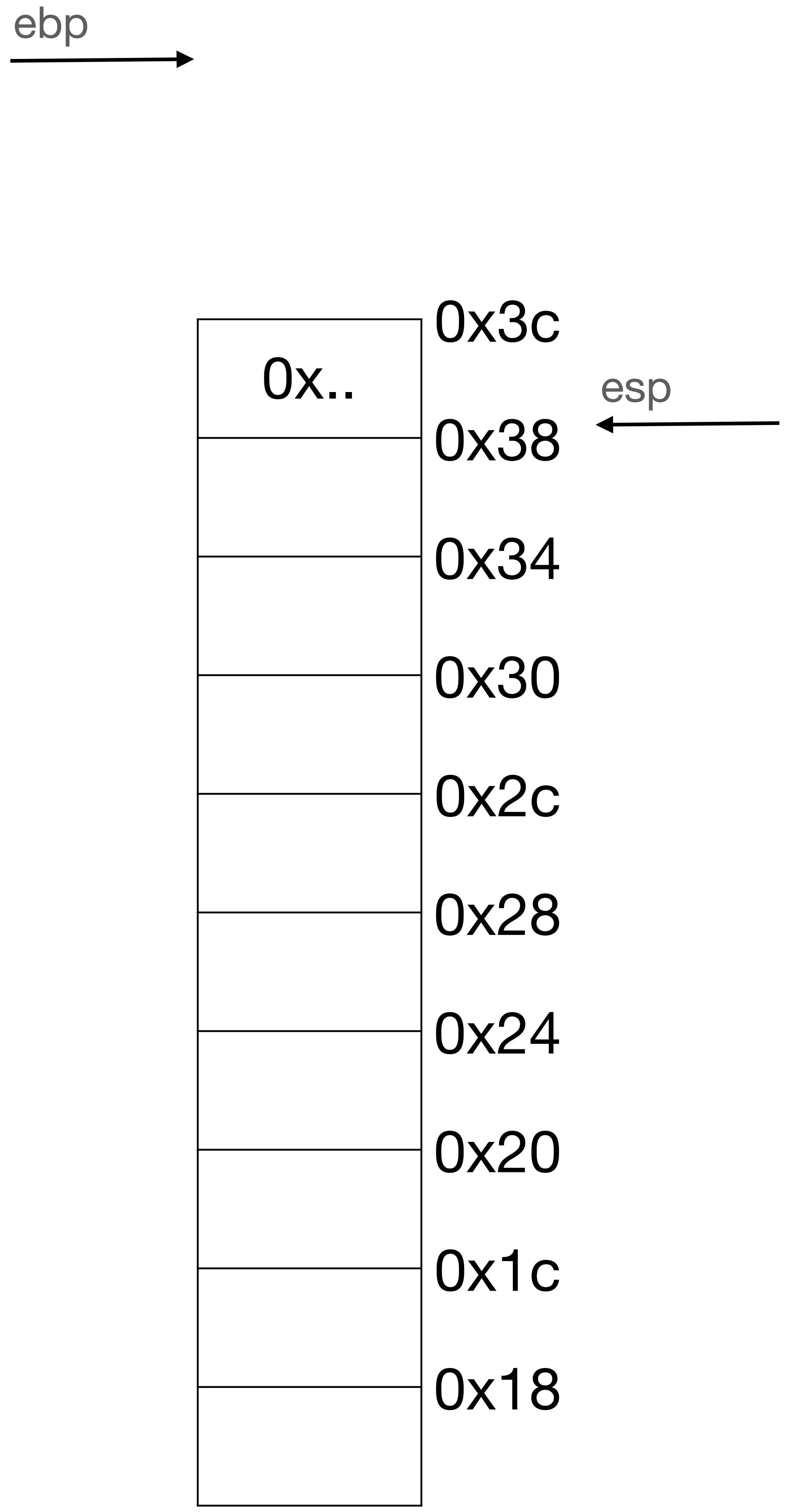
eip



Function calling in action: Stack



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Function calling in action: Stack

eip

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02.s

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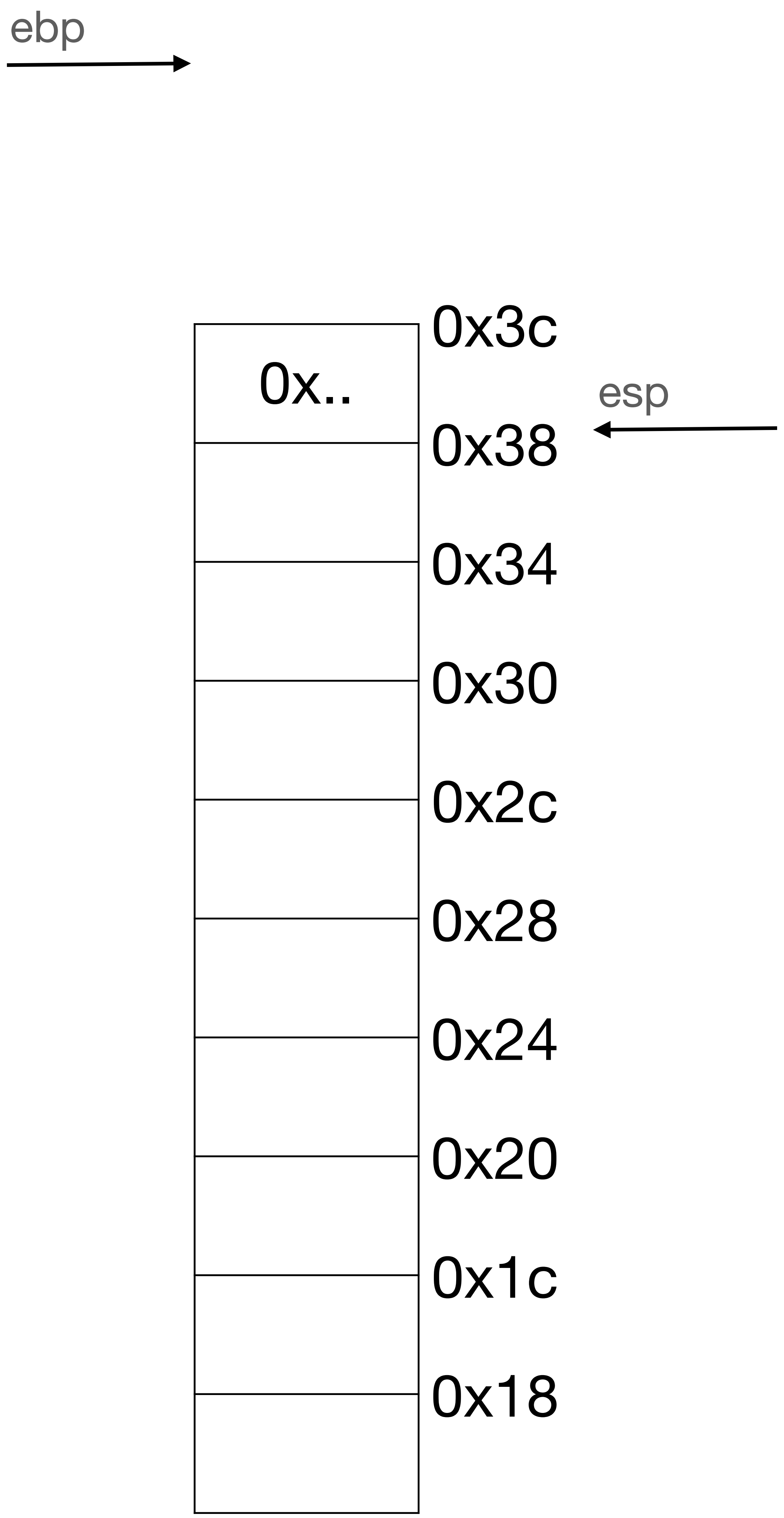
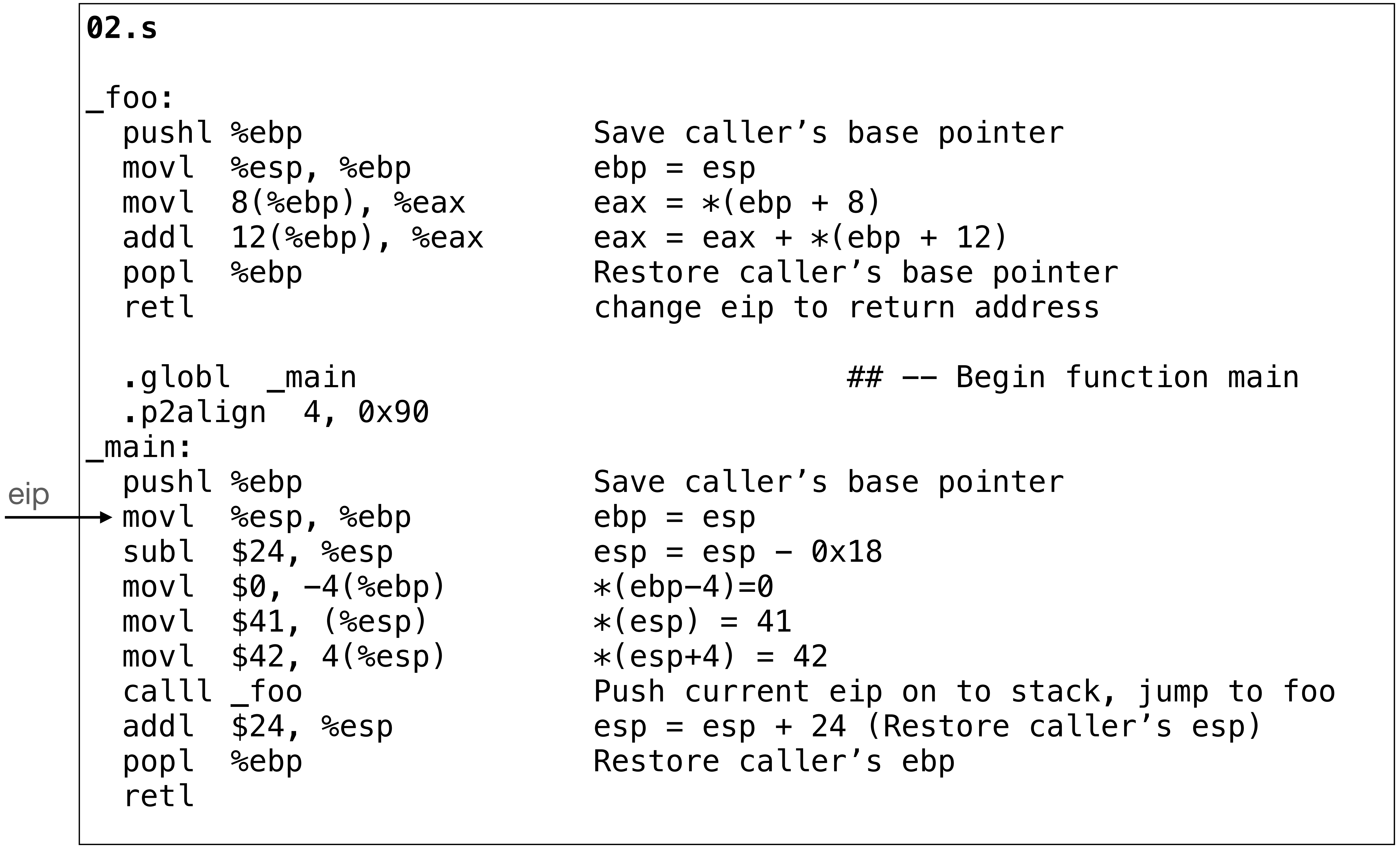


Function calling in action: Stack



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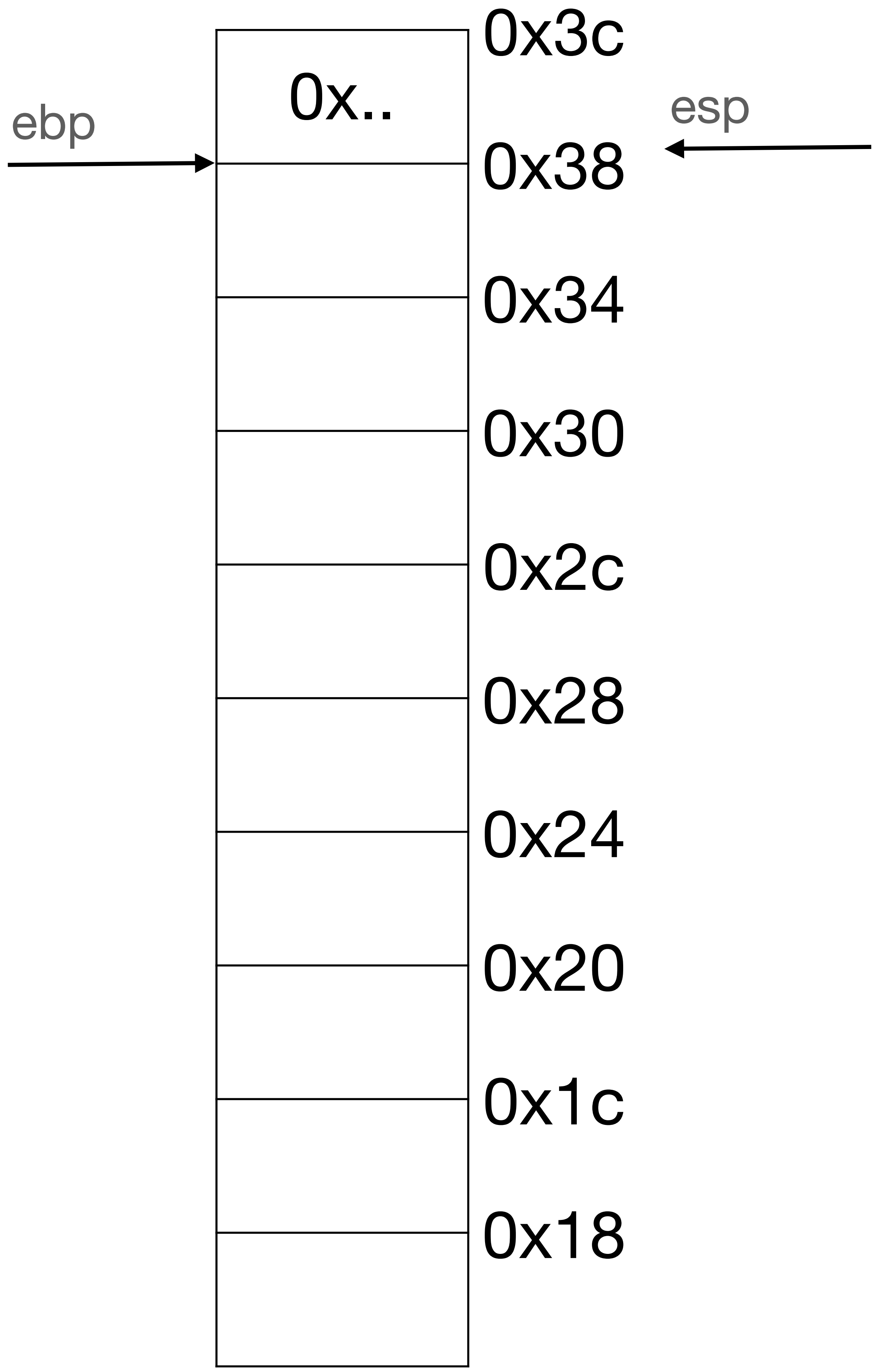

Function calling in action: Stack

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02.s

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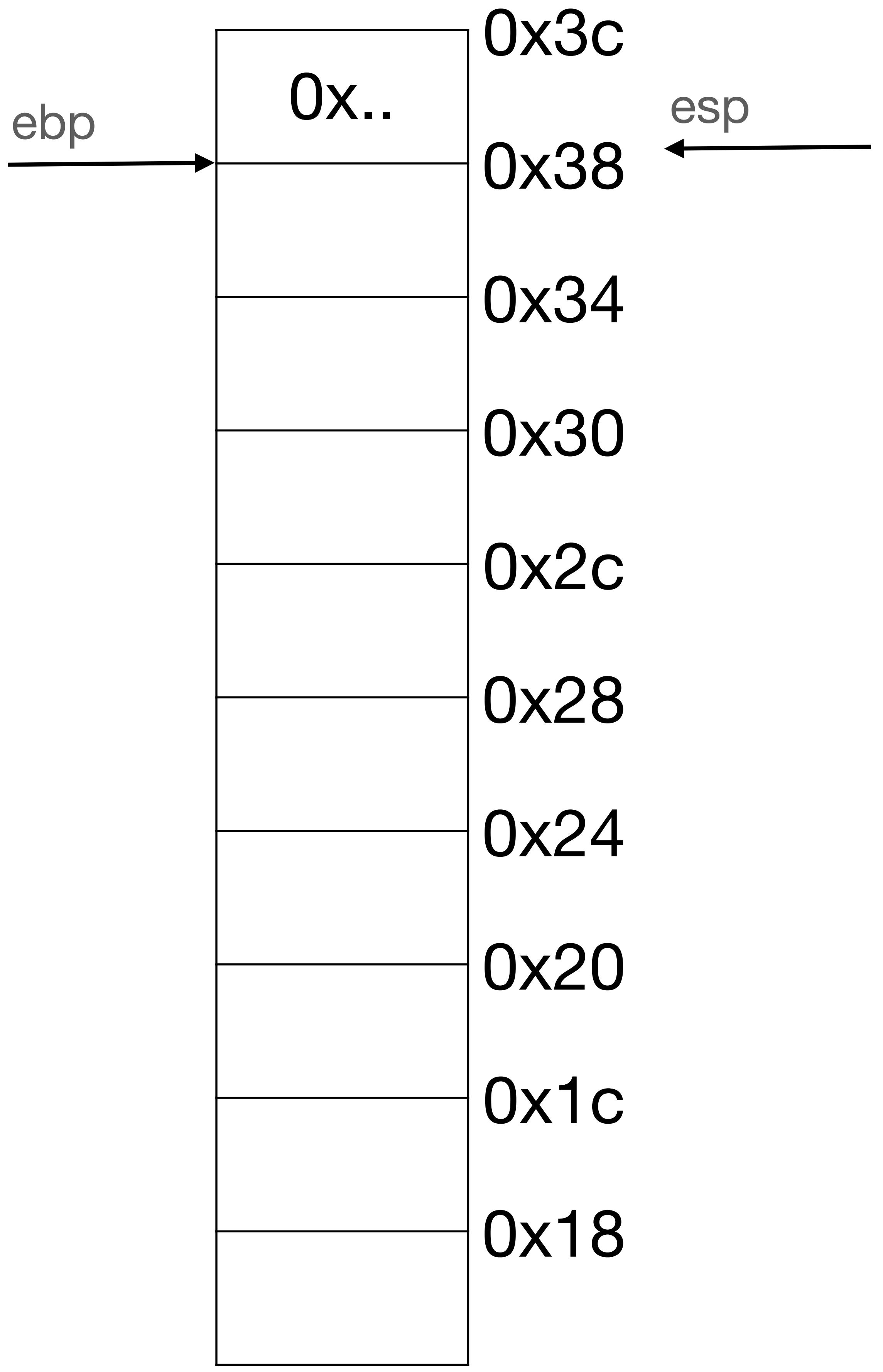
eip



Function calling in action: Stack

02.s

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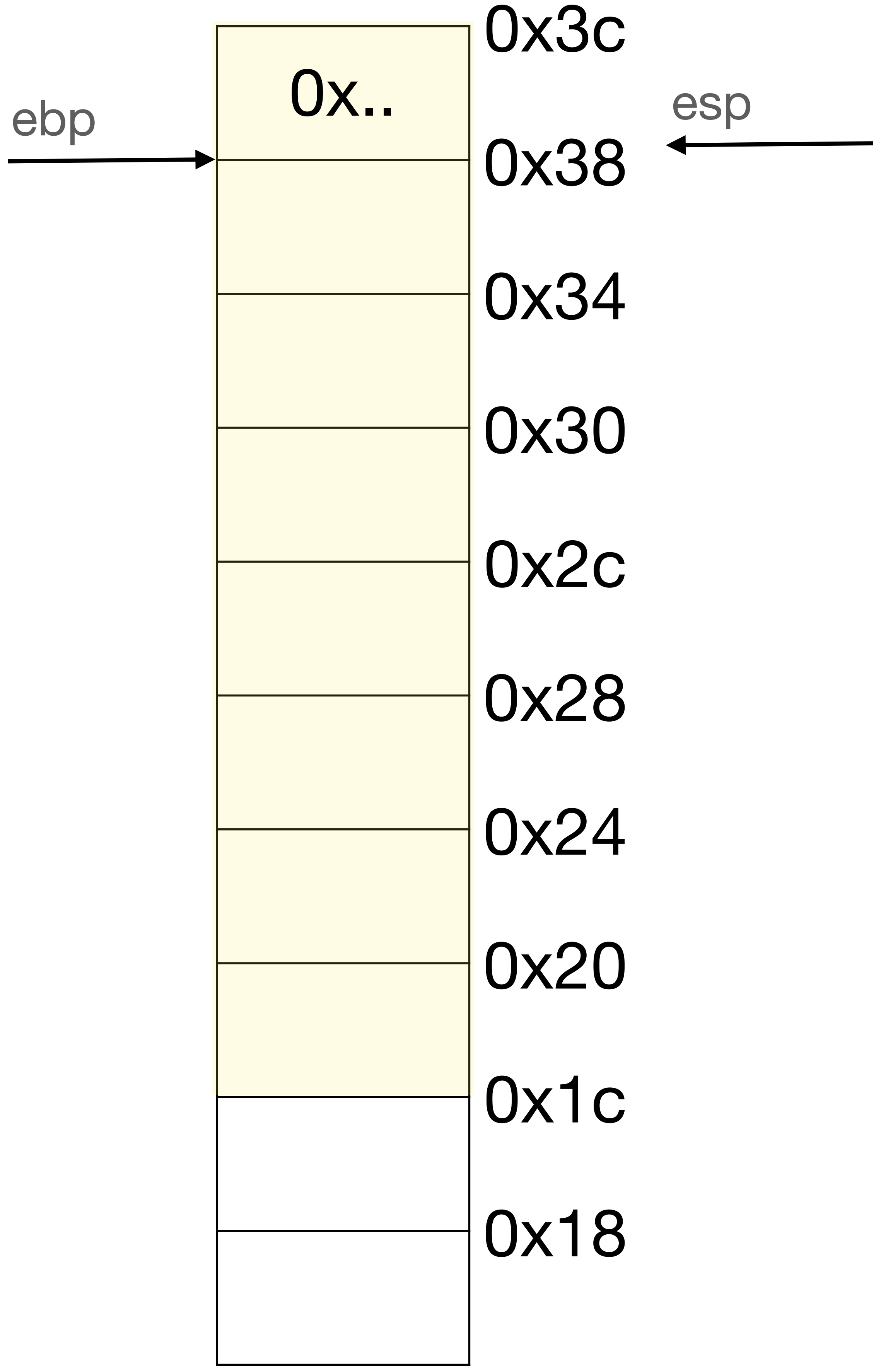

Function calling in action: Stack

02.s

eip

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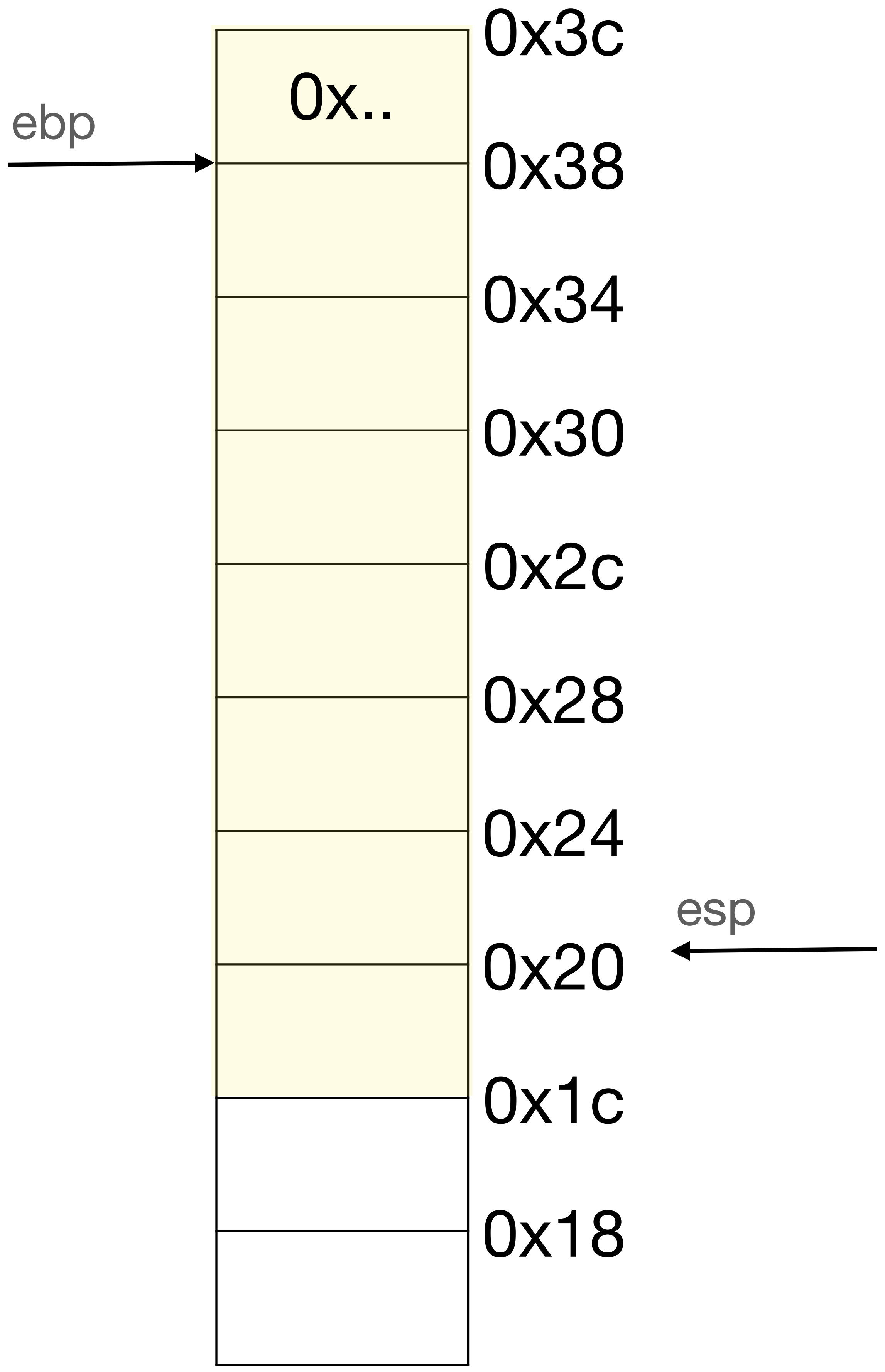

Function calling in action: Stack

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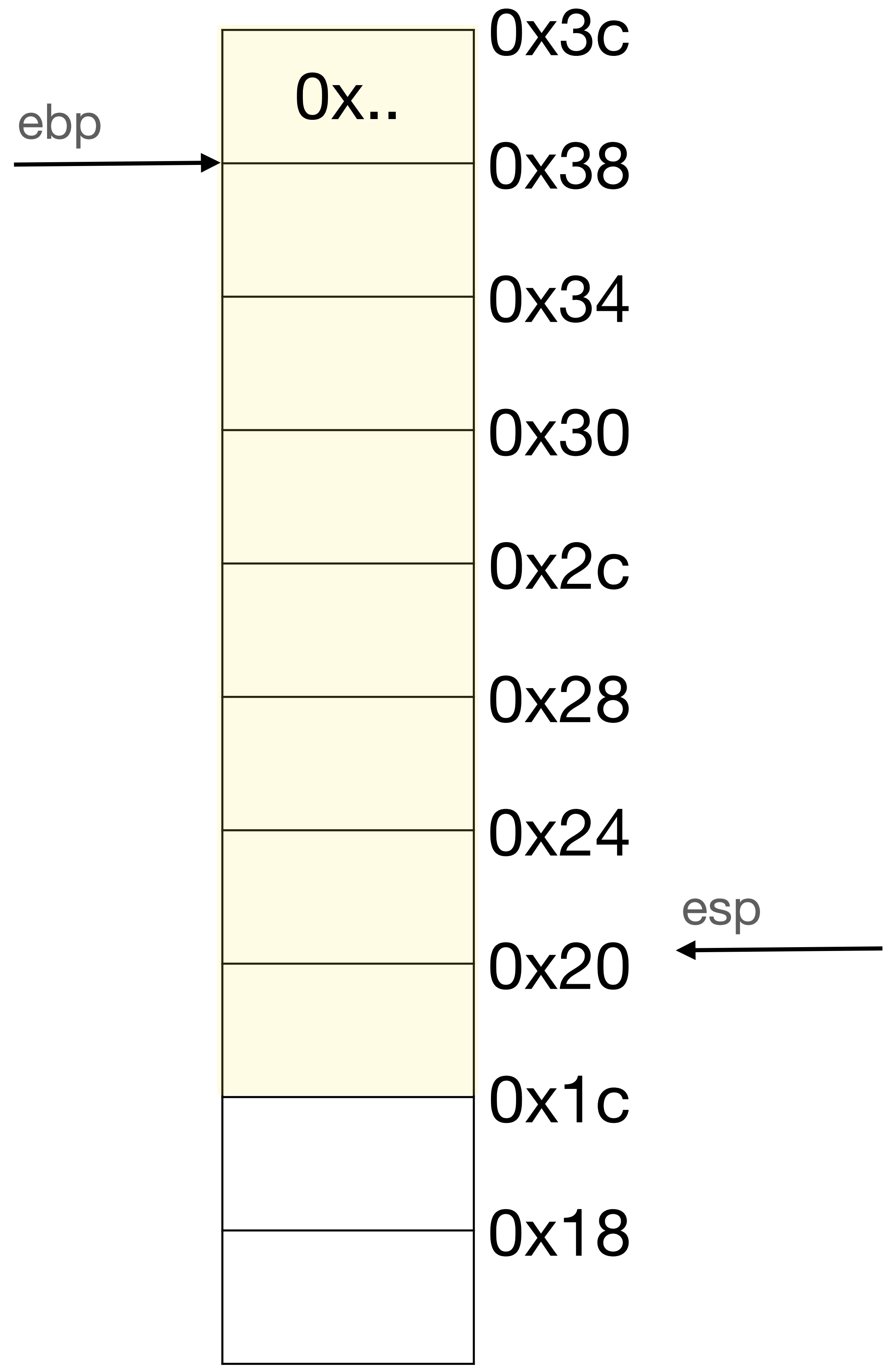
eip



Function calling in action: Stack

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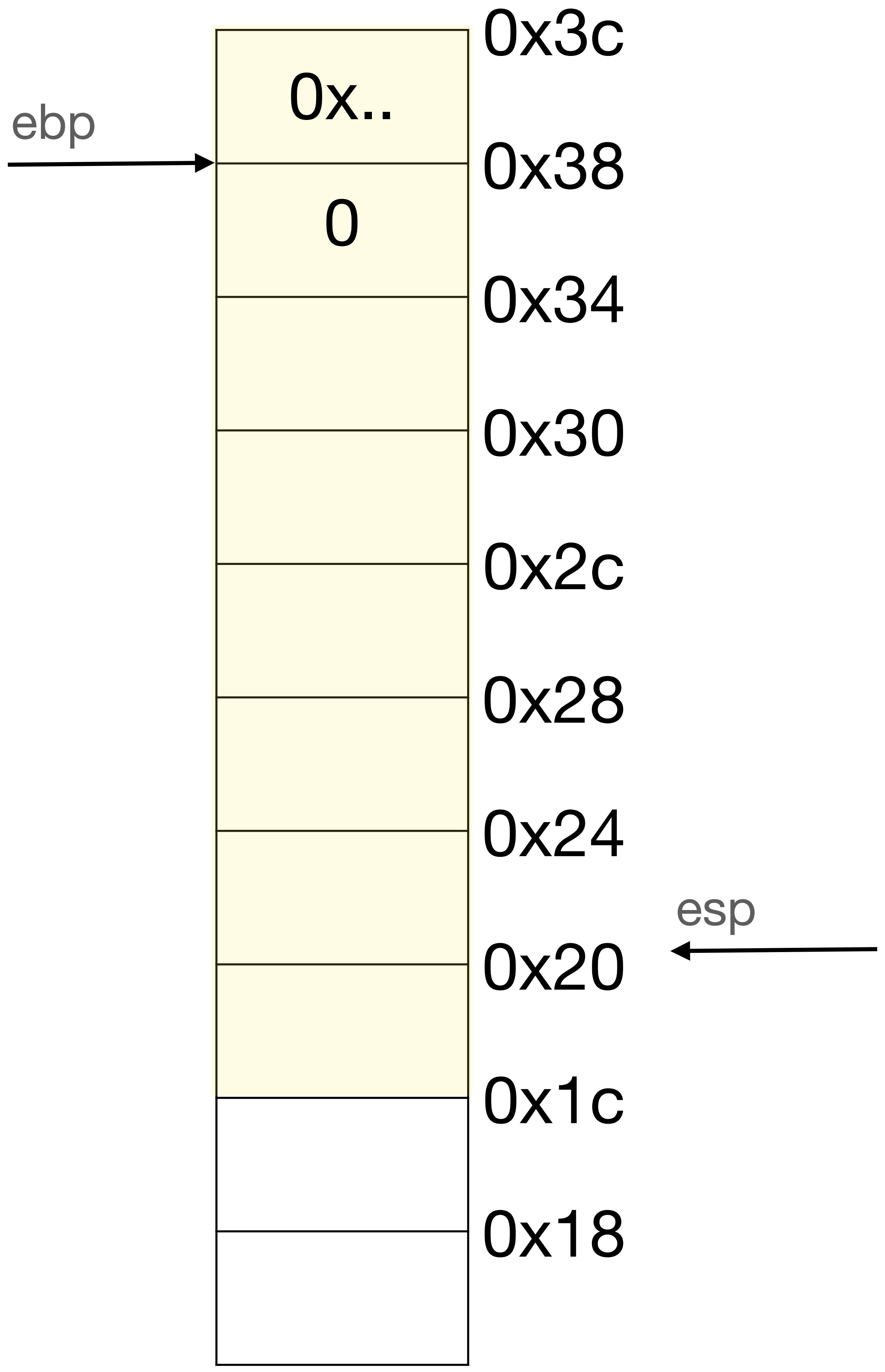
eip →



Function calling in action: Stack

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02.s

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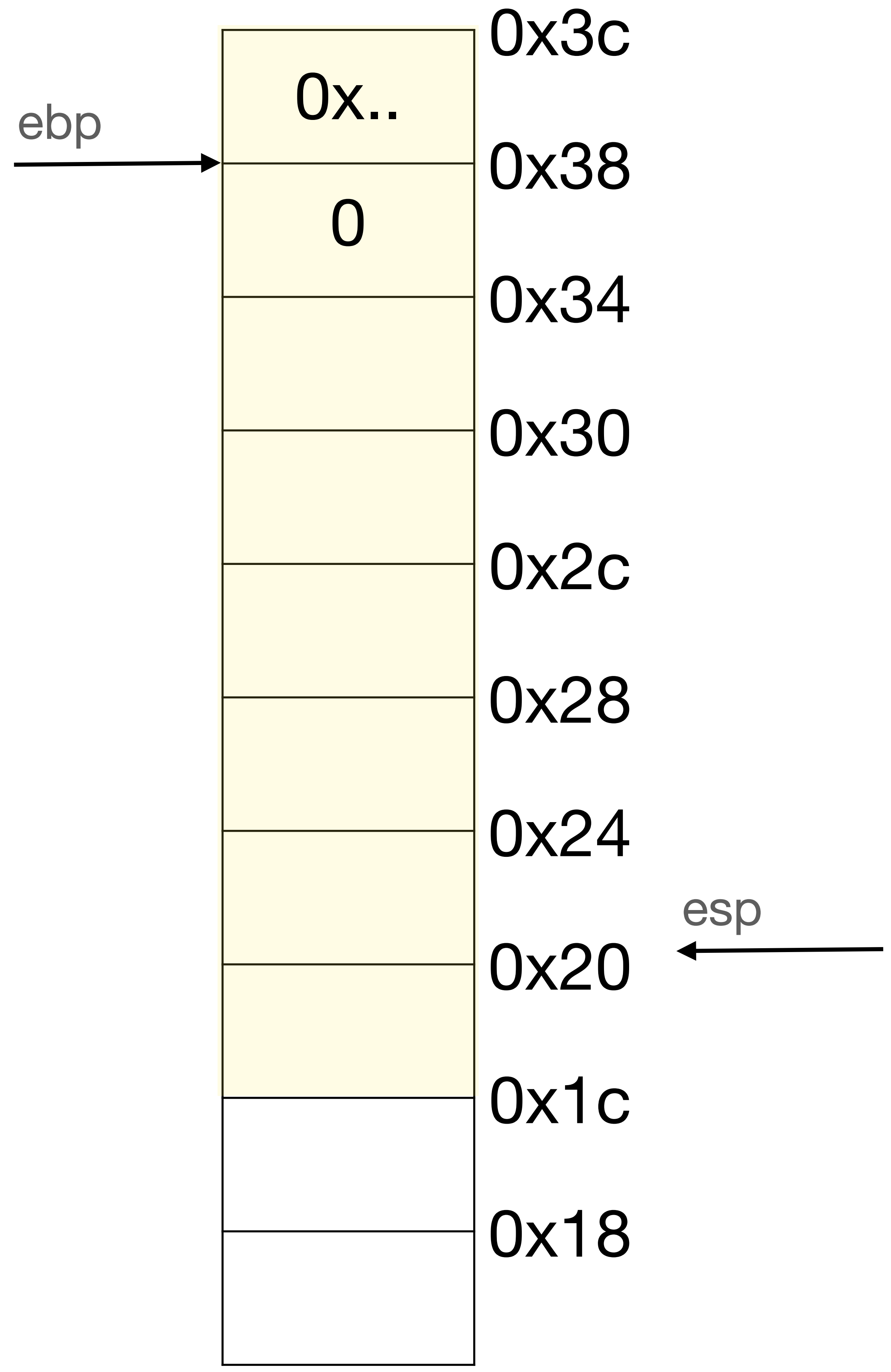
eip → movl $41, (%esp)



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02.s

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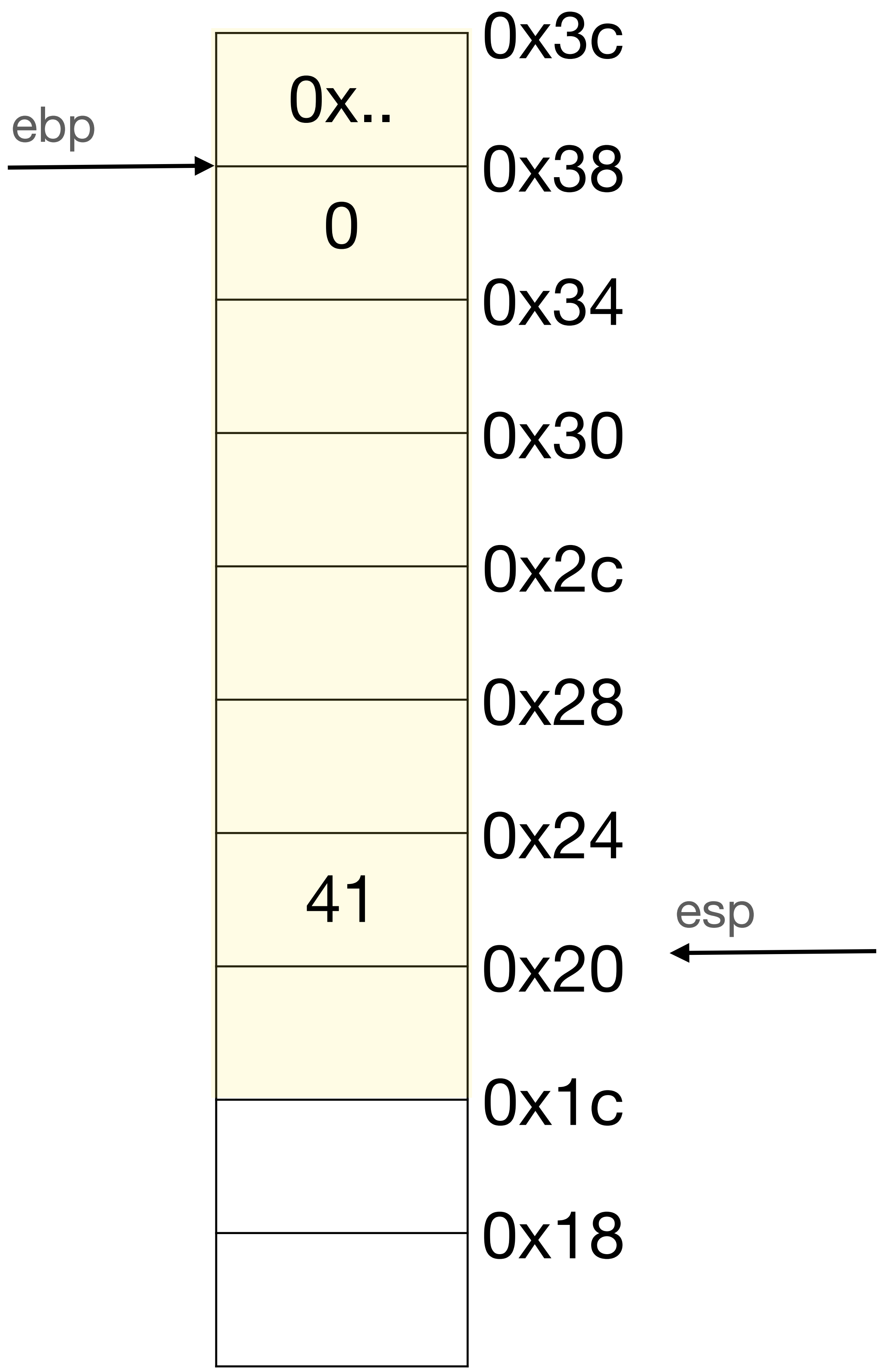
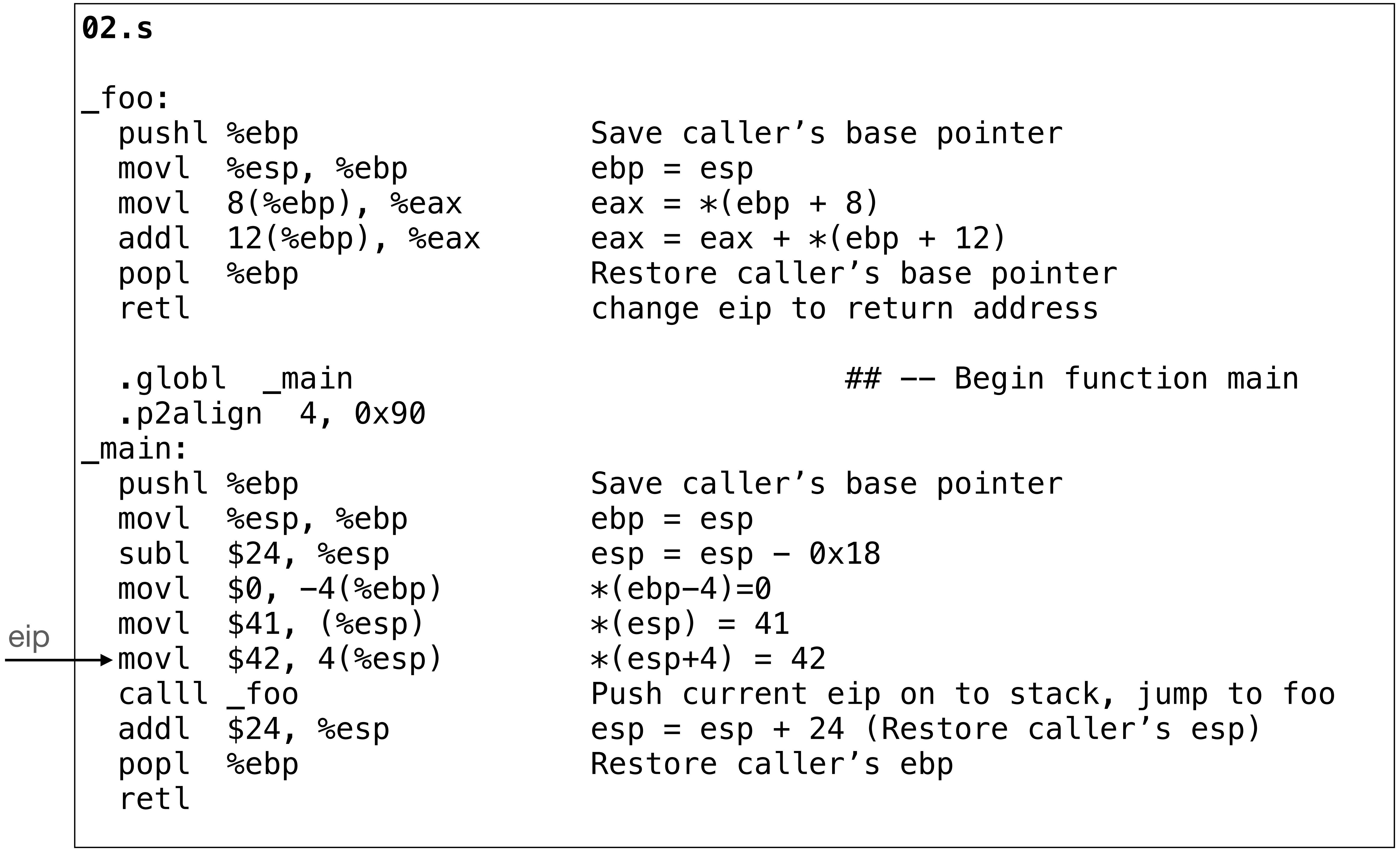
eip → movl $41, (%esp)



Function calling in action: Stack



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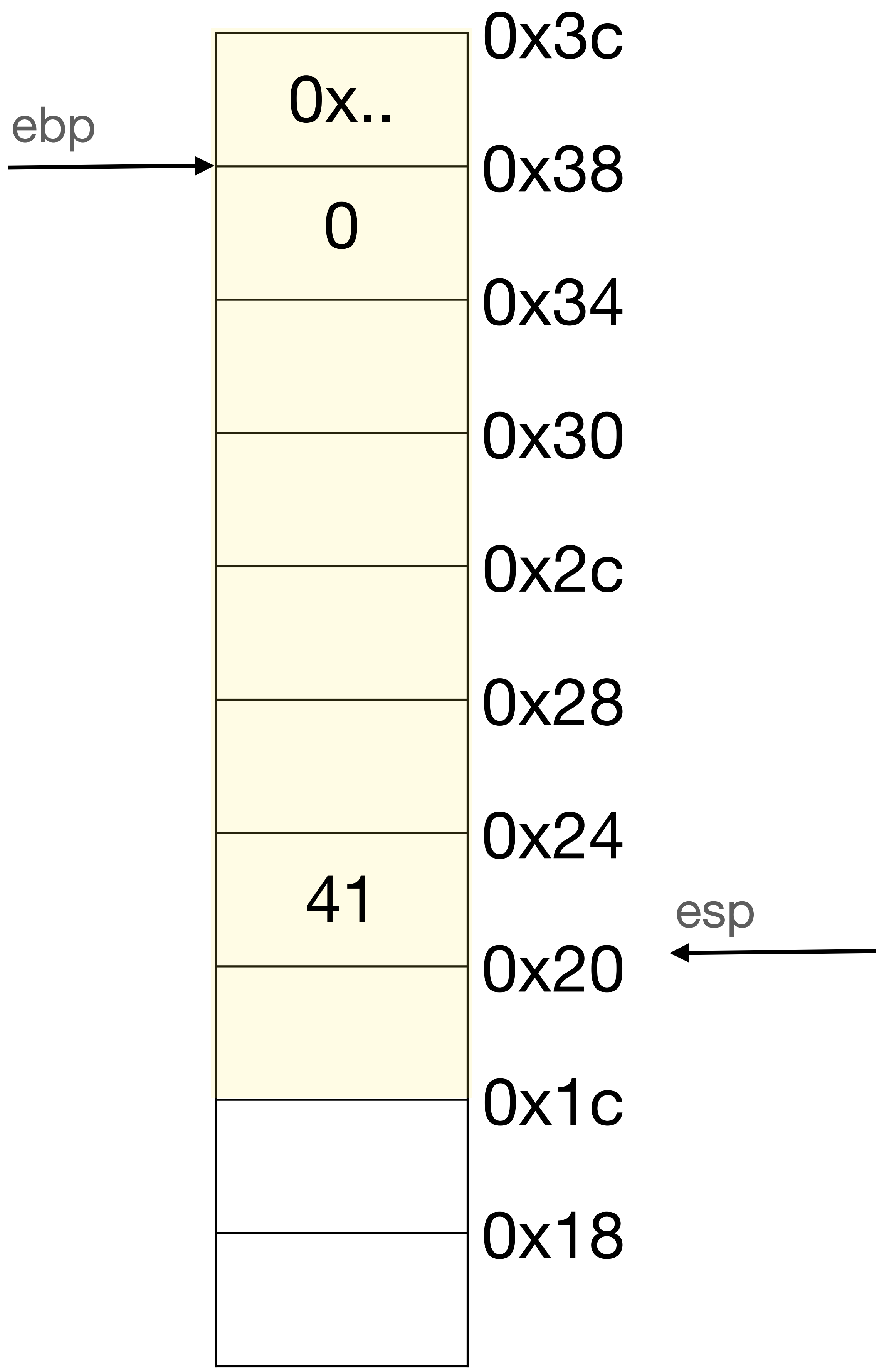

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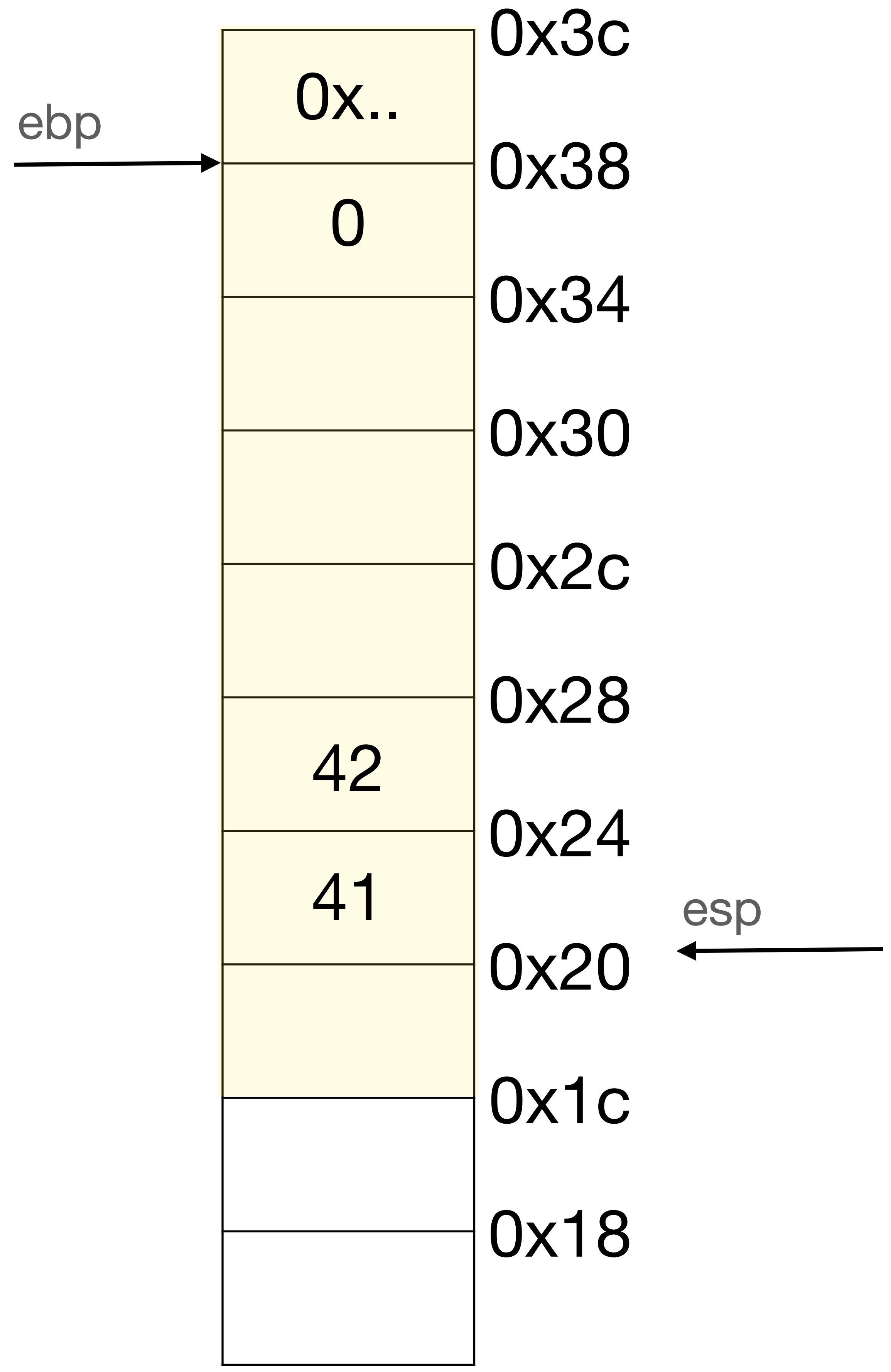

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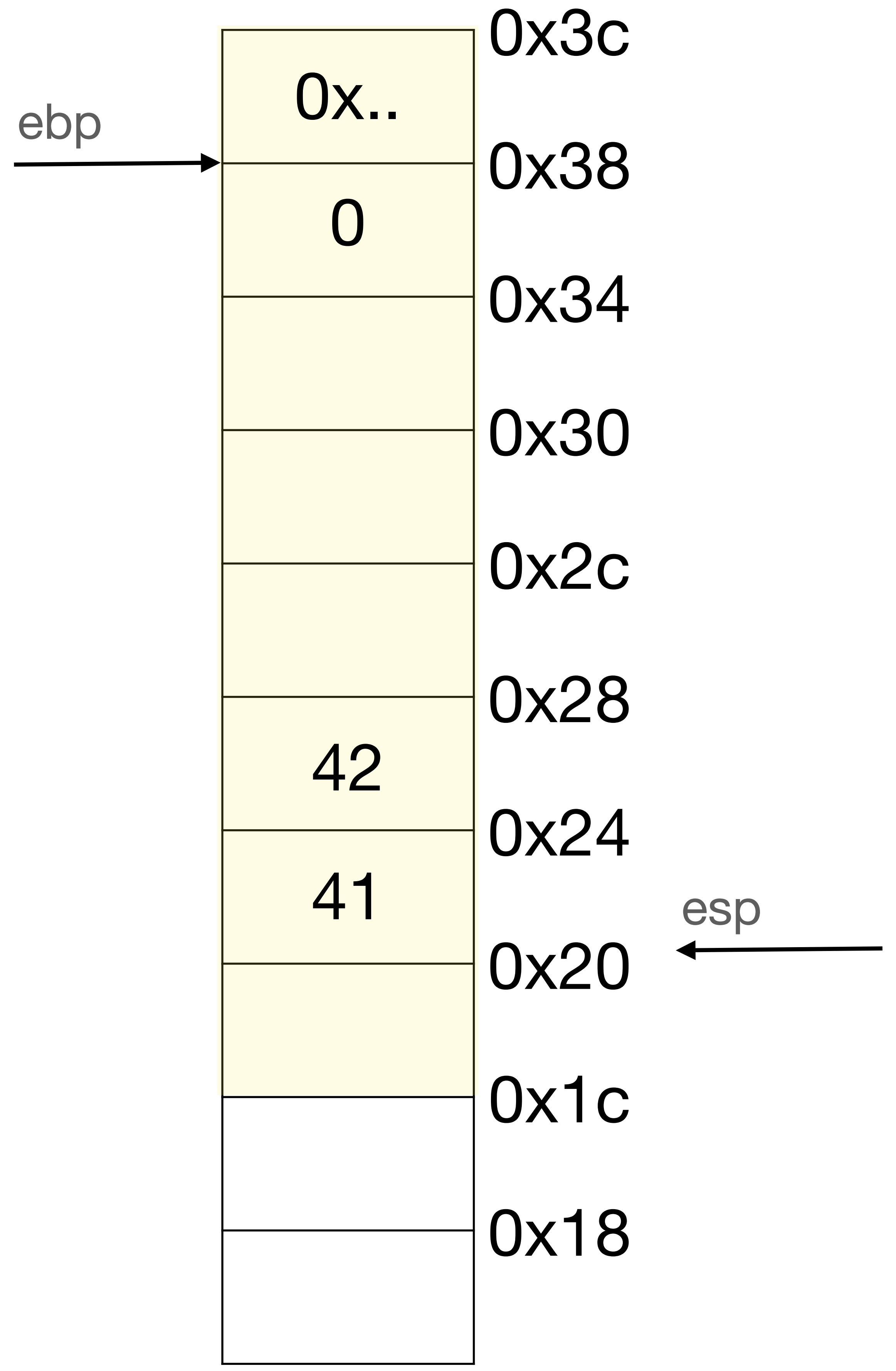
eip



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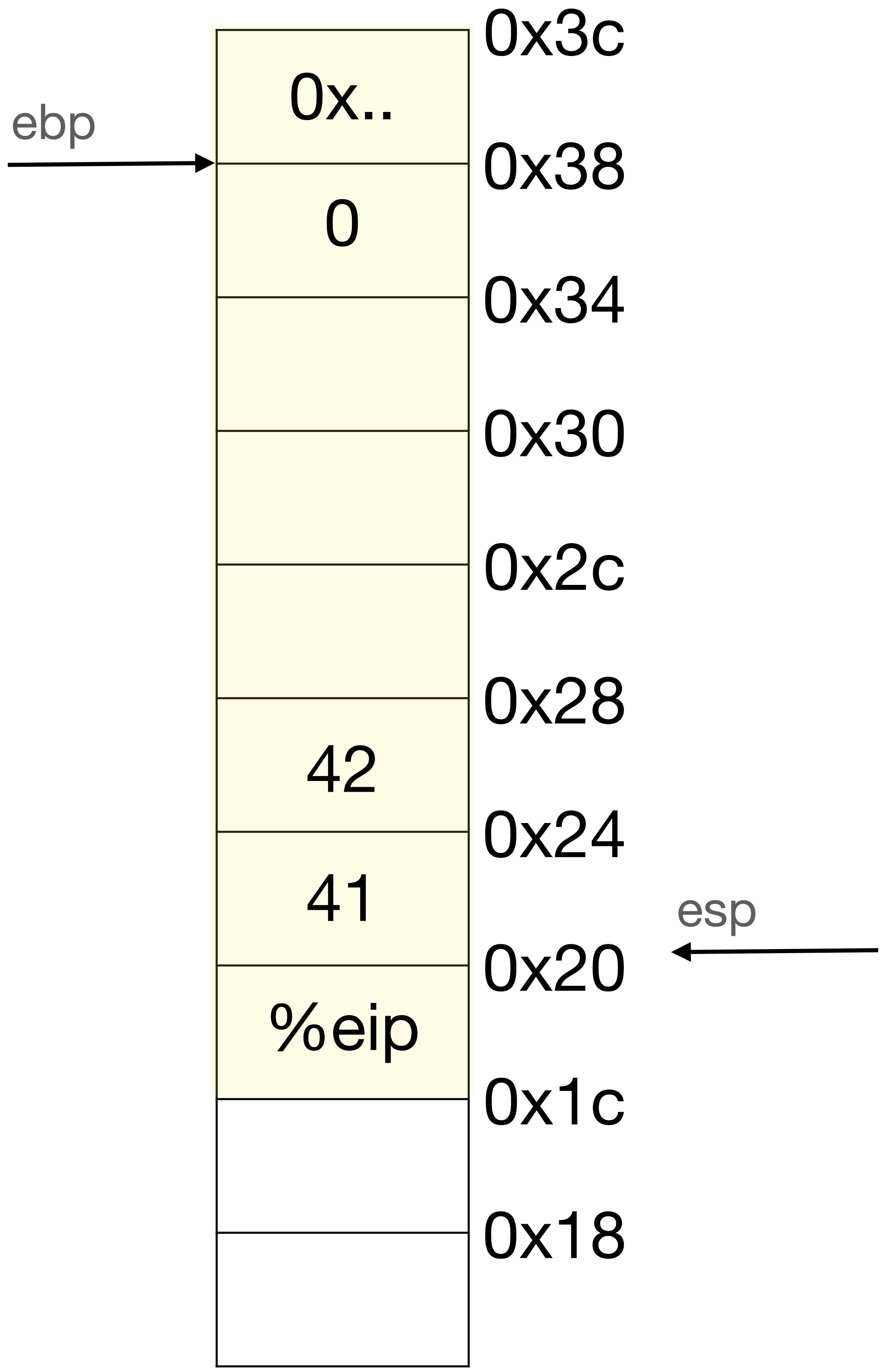
eip



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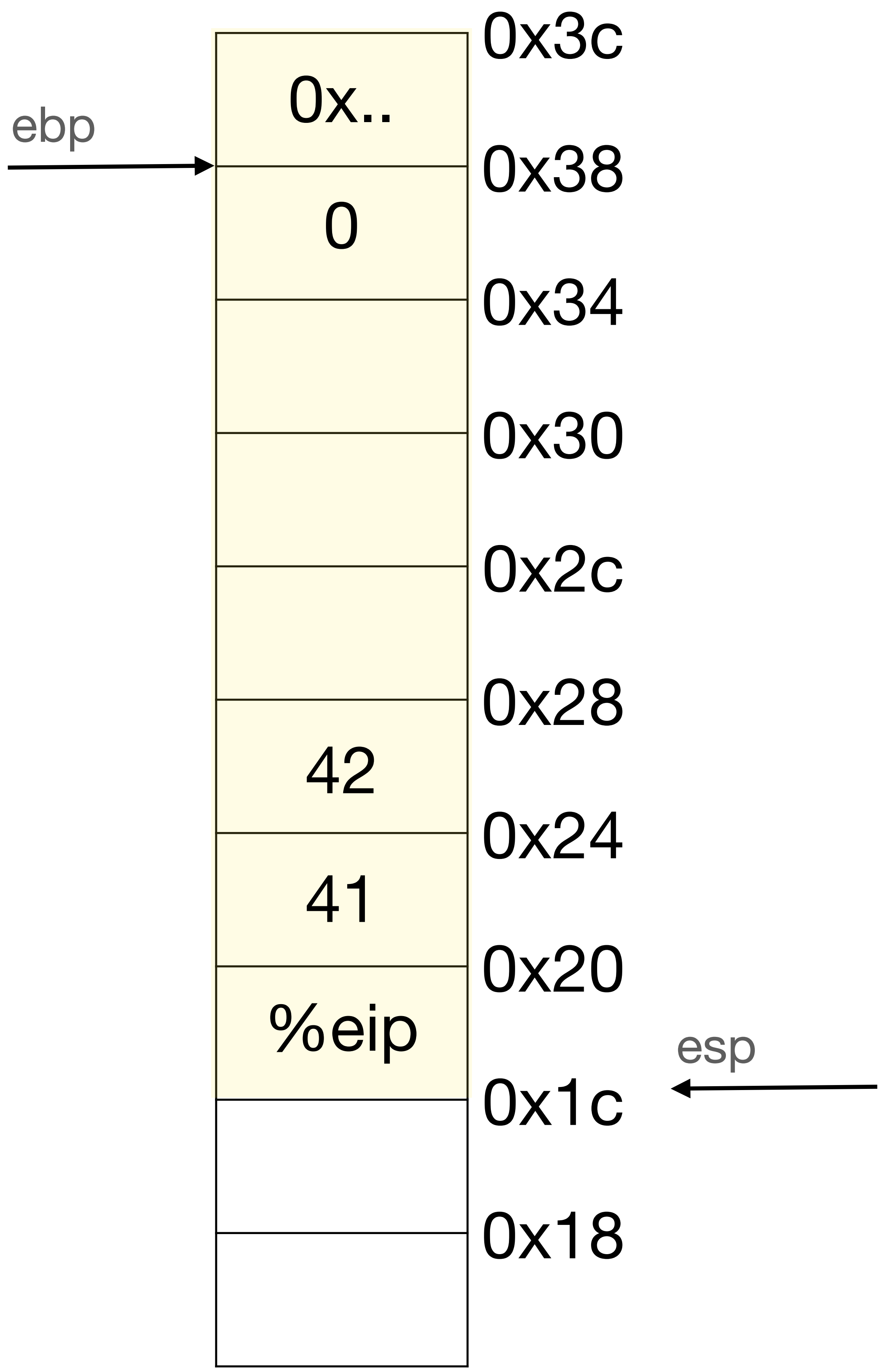
  pushl %ebp                Save caller’s base pointer
  movl  %esp, %ebp          ebp = esp
  subl  $24, %esp           esp = esp - 0x18
  movl  $0, -4(%ebp)        *(ebp-4)=0
  movl  $41, (%esp)         *(esp) = 41
  movl  $42, 4(%esp)        *(esp+4) = 42
  calll _foo                Push current eip on to stack, jump to foo
  addl  $24, %esp           esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                Restore caller’s ebp
  retl
```

eip

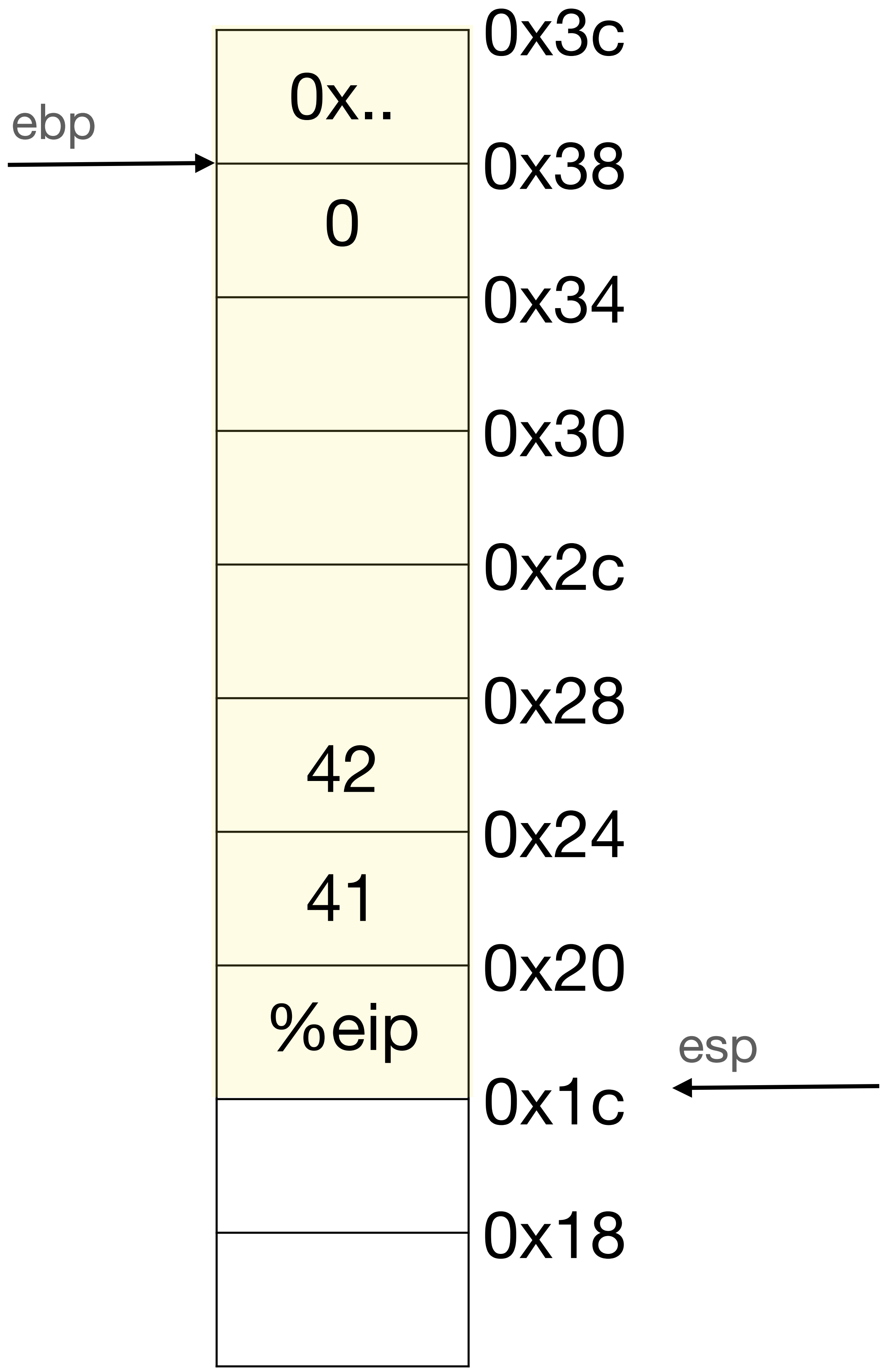


Function calling in action: Stack

```
02.s

_foo:
eip → pushl %ebp              Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
  popl  %ebp                  Restore caller’s base pointer
  retl                        change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  subl  $24, %esp             esp = esp - 0x18
  movl  $0, -4(%ebp)          *(ebp-4)=0
  movl  $41, (%esp)           *(esp) = 41
  movl  $42, 4(%esp)          *(esp+4) = 42
  calll _foo                  Push current eip on to stack, jump to foo
  addl  $24, %esp             esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                  Restore caller’s ebp
  retl
```



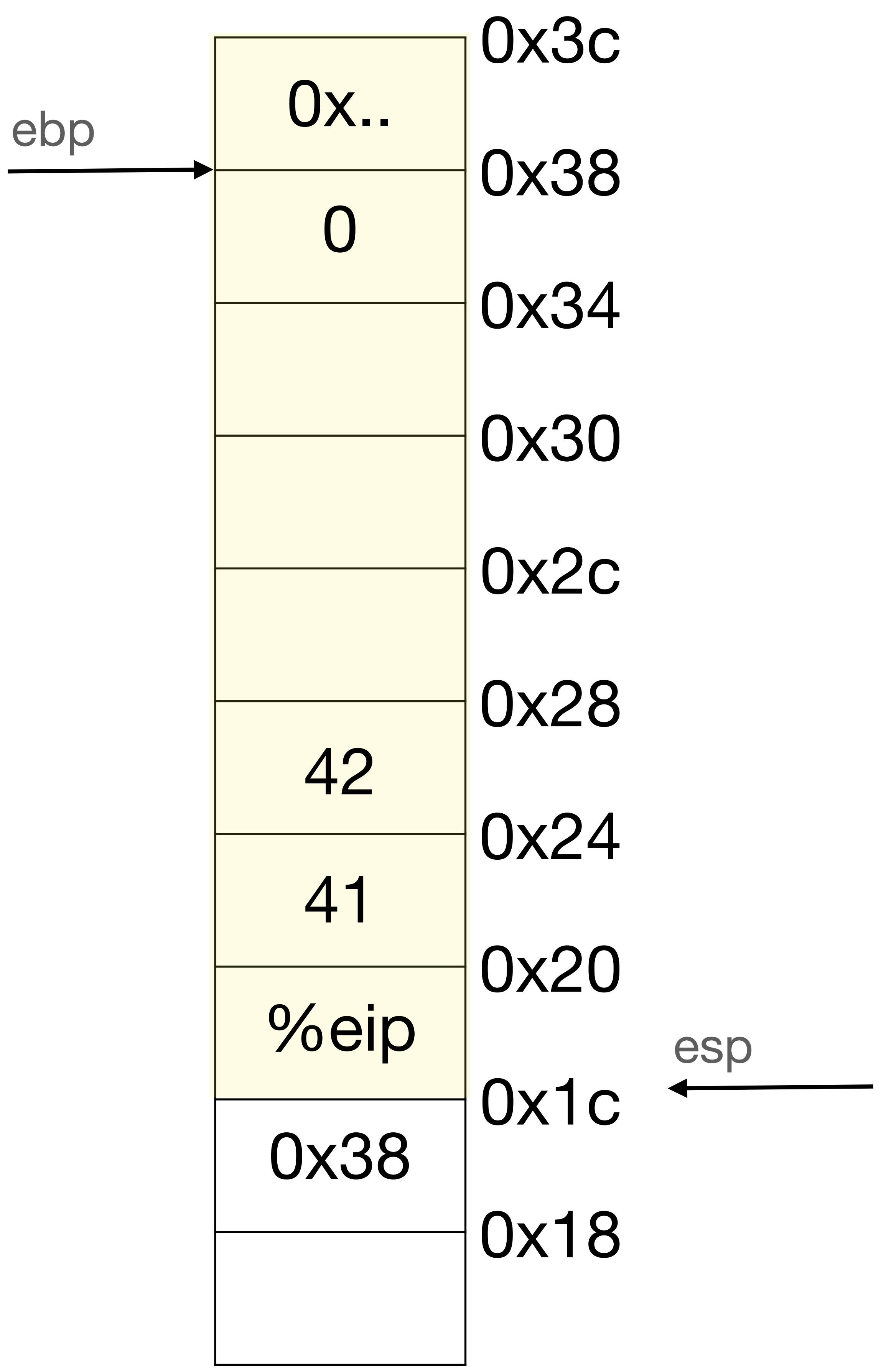
Function calling in action: Stack

eip

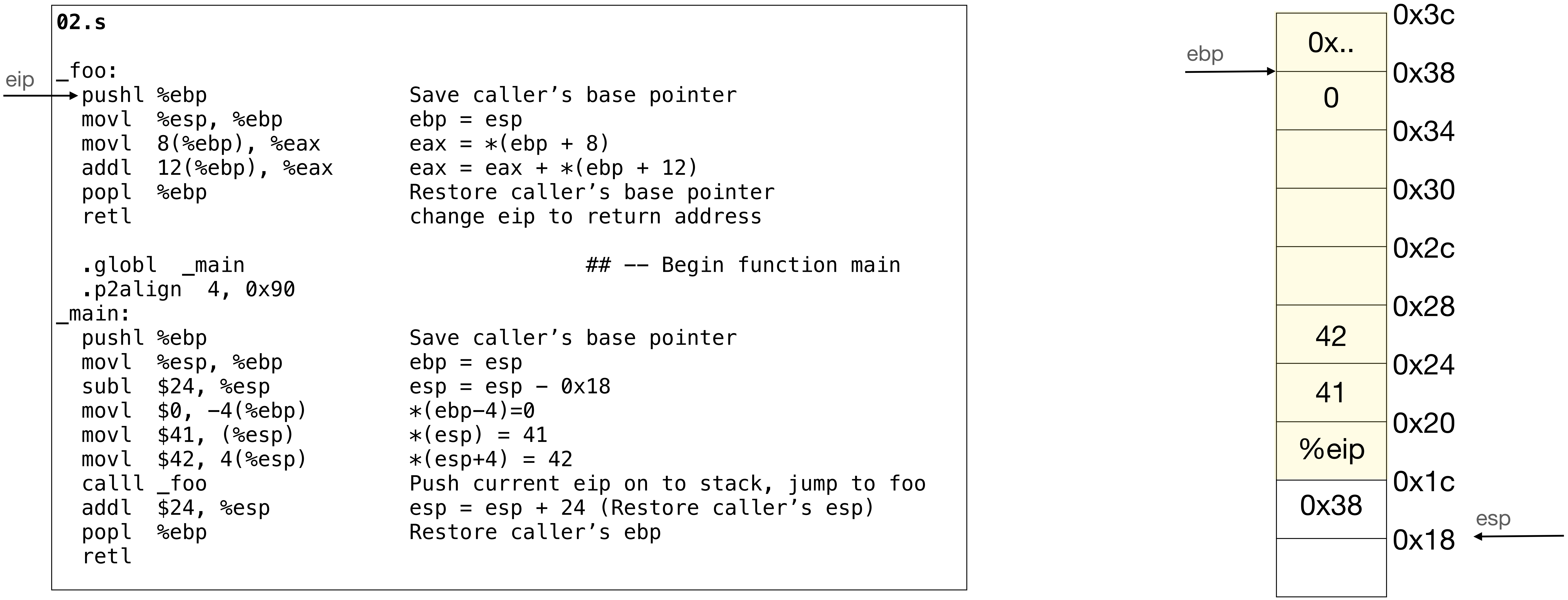
```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = *(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + *(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp - 0x18
  movl  $0, -4(%ebp)         *(ebp-4)=0
  movl  $41, (%esp)          *(esp) = 41
  movl  $42, 4(%esp)         *(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```



Function calling in action: Stack



02.s

```
_foo:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
  popl  %ebp                  Restore caller’s base pointer
  retl                        change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  subl  $24, %esp             esp = esp - 0x18
  movl  $0, -4(%ebp)          *(ebp-4)=0
  movl  $41, (%esp)           *(esp) = 41
  movl  $42, 4(%esp)          *(esp+4) = 42
  calll _foo                  Push current eip on to stack, jump to foo
  addl  $24, %esp             esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                  Restore caller’s ebp
  retl
```

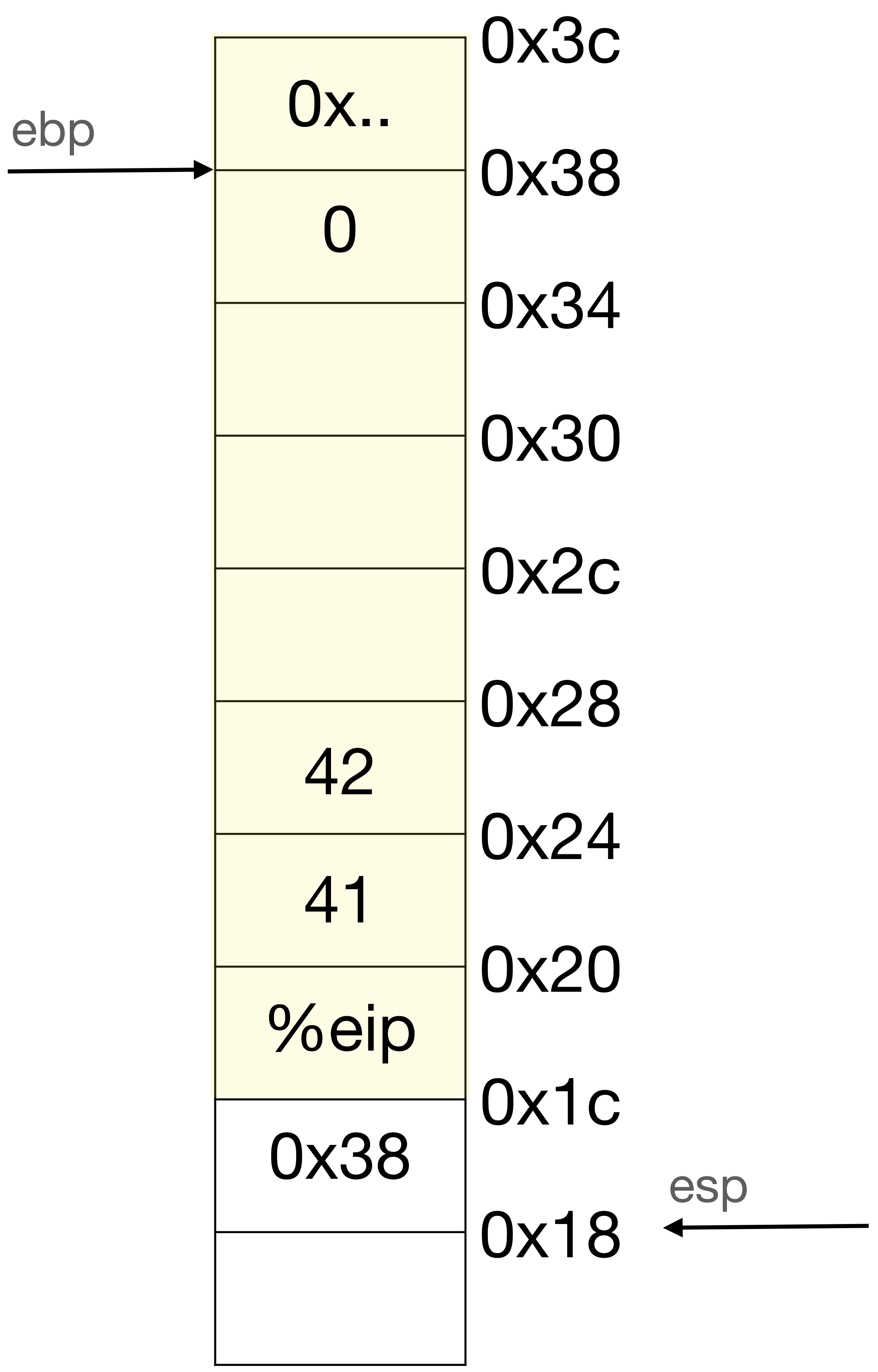
Function calling in action: Stack

eip

```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = ∗(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + ∗(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp - 0x18
  movl  $0, -4(%ebp)         ∗(ebp-4)=0
  movl  $41, (%esp)          ∗(esp) = 41
  movl  $42, 4(%esp)         ∗(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```



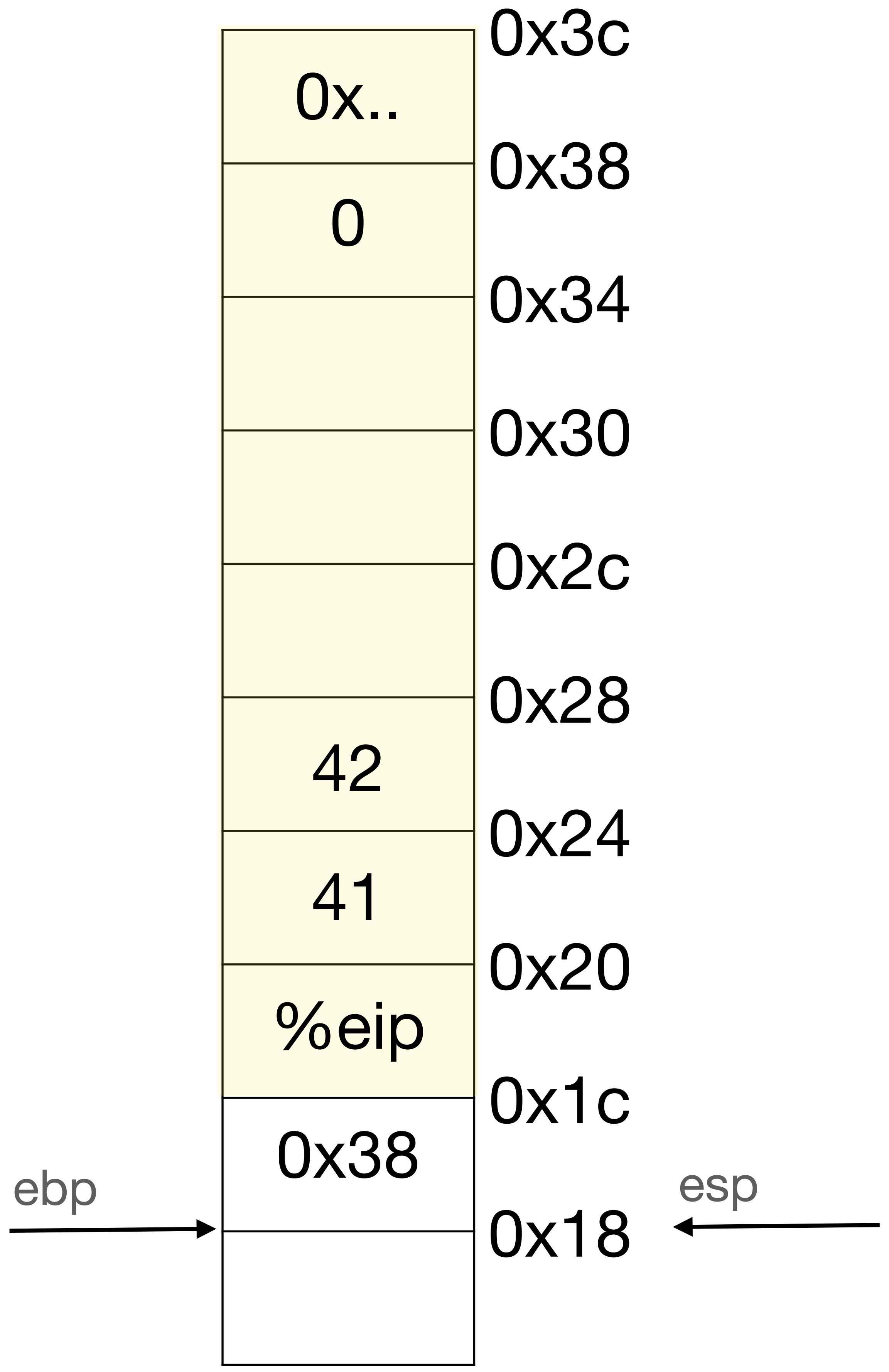
Function calling in action: Stack

eip

```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = *(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + *(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                            ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp - 0x18
  movl  $0, -4(%ebp)         *(ebp-4)=0
  movl  $41, (%esp)          *(esp) = 41
  movl  $42, 4(%esp)         *(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```

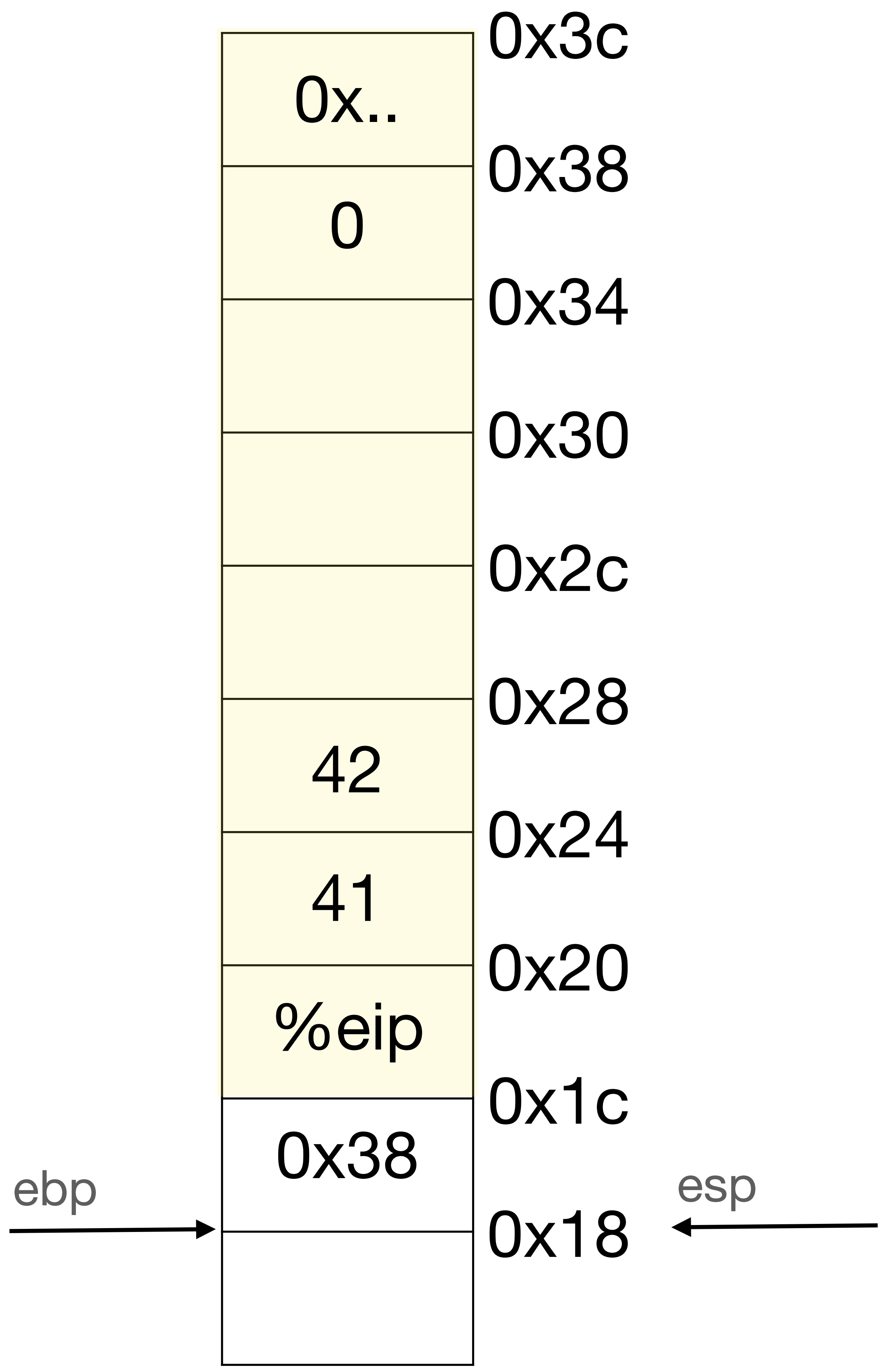


Function calling in action: Stack

02.s

```
       _foo:
         pushl %ebp                    Save caller’s base pointer
         movl  %esp, %ebp              ebp = esp
eip →    movl  8(%ebp), %eax           eax = ∗(ebp + 8)
         addl  12(%ebp), %eax          eax = eax + ∗(ebp + 12)
         popl  %ebp                    Restore caller’s base pointer
         retl                          change eip to return address

         .globl  _main                               ## -- Begin function main
         .p2align  4, 0x90
       _main:
         pushl %ebp                    Save caller’s base pointer
         movl  %esp, %ebp              ebp = esp
         subl  $24, %esp               esp = esp − 0x18
         movl  $0, -4(%ebp)            ∗(ebp−4)=0
         movl  $41, (%esp)             ∗(esp) = 41
         movl  $42, 4(%esp)            ∗(esp+4) = 42
         calll _foo                    Push current eip on to stack, jump to foo
         addl  $24, %esp               esp = esp + 24 (Restore caller’s esp)
         popl  %ebp                    Restore caller’s ebp
         retl
```



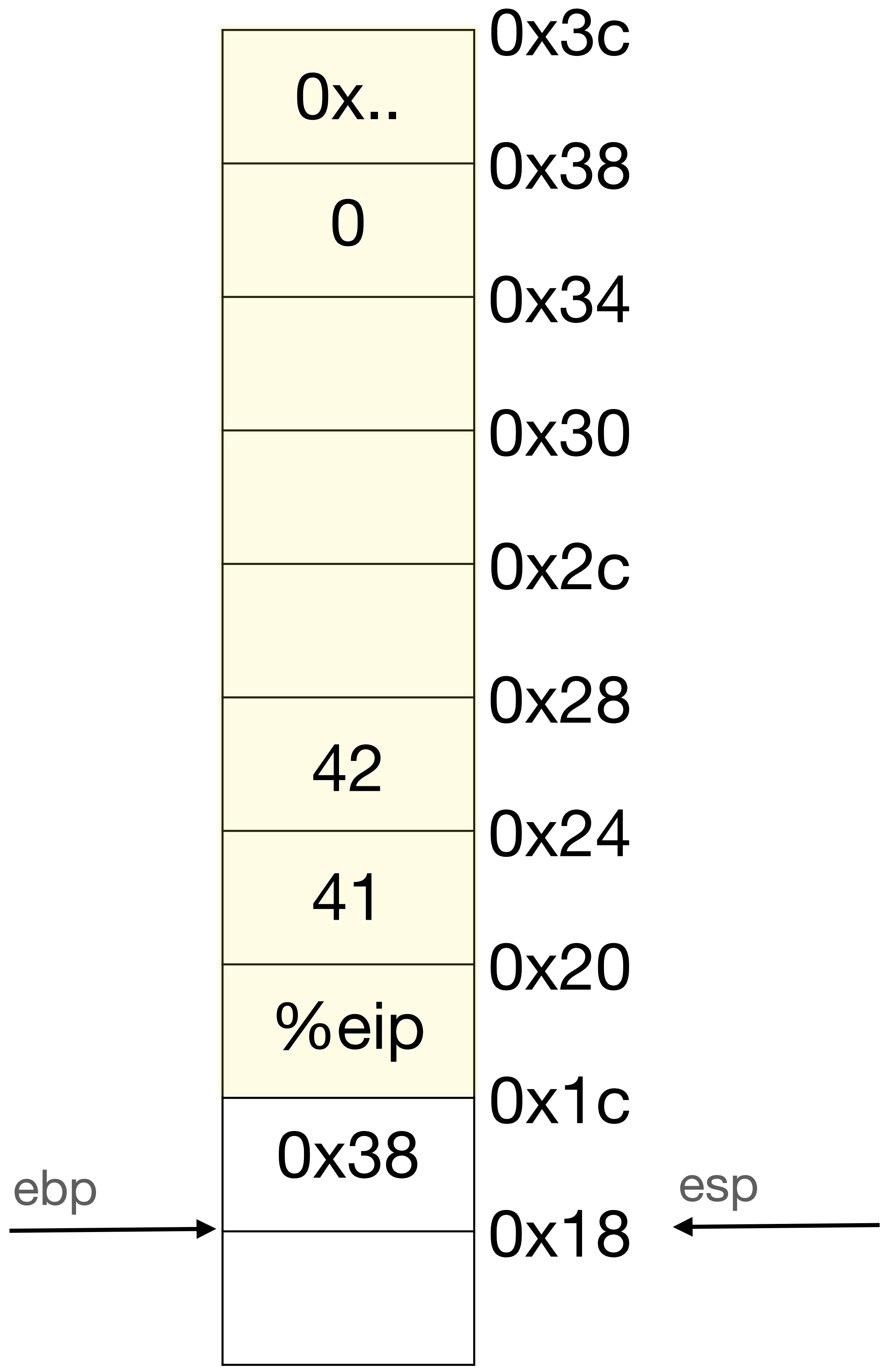
Function calling in action: Stack

eip

```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = ∗(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + ∗(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp − 0x18
  movl  $0, −4(%ebp)         ∗(ebp−4)=0
  movl  $41, (%esp)          ∗(esp) = 41
  movl  $42, 4(%esp)         ∗(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```



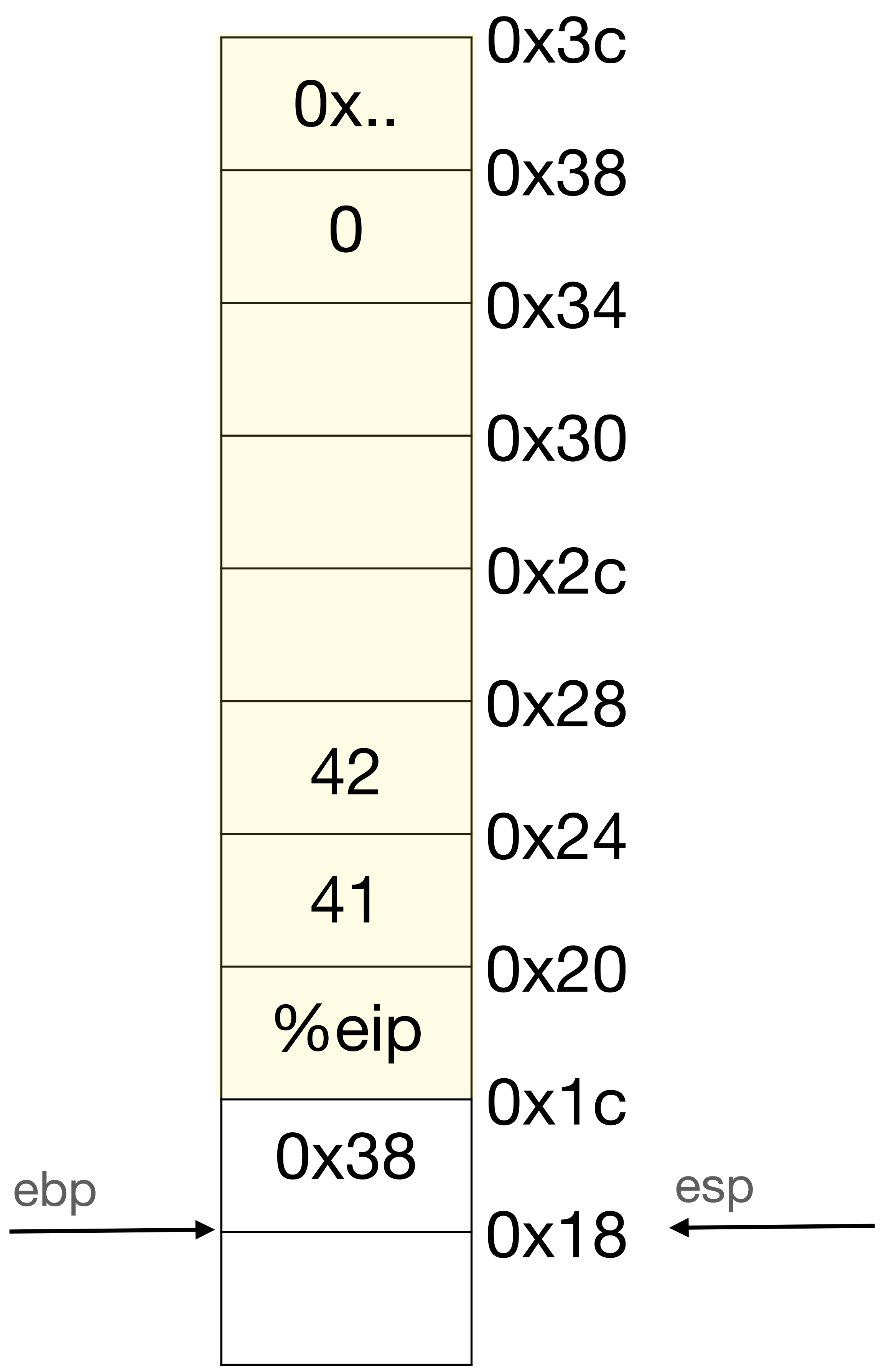
Function calling in action: Stack

eip

```
02.s

_foo:
  pushl %ebp                Save caller’s base pointer
  movl  %esp, %ebp          ebp = esp
  movl  8(%ebp), %eax       eax = ∗(ebp + 8)
  addl  12(%ebp), %eax      eax = eax + ∗(ebp + 12)
  popl  %ebp                Restore caller’s base pointer
  retl                      change eip to return address

  .globl  _main                           ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                Save caller’s base pointer
  movl  %esp, %ebp          ebp = esp
  subl  $24, %esp           esp = esp − 0x18
  movl  $0, −4(%ebp)        ∗(ebp−4)=0
  movl  $41, (%esp)         ∗(esp) = 41
  movl  $42, 4(%esp)        ∗(esp+4) = 42
  calll _foo                Push current eip on to stack, jump to foo
  addl  $24, %esp           esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                Restore caller’s ebp
  retl
```



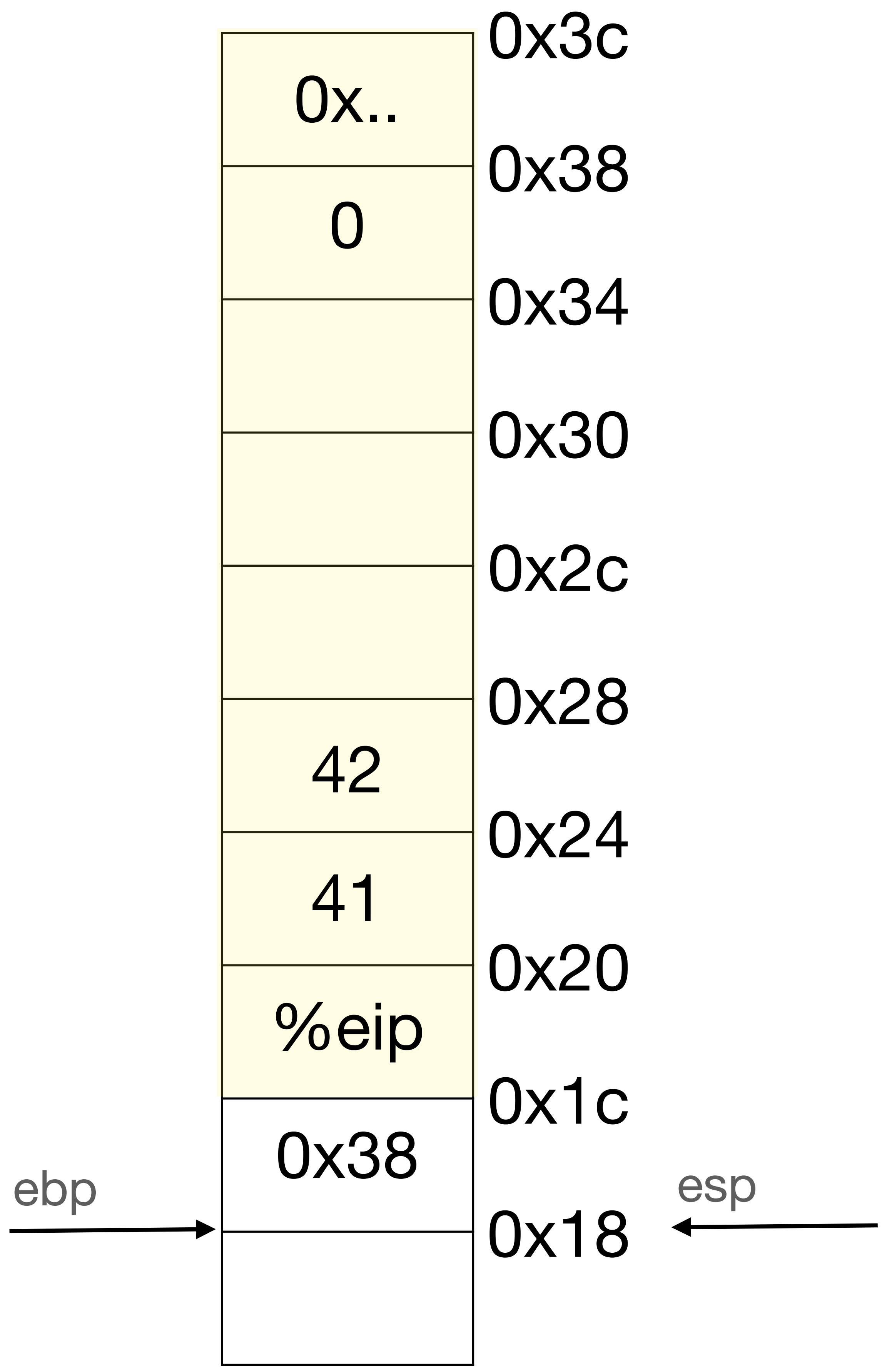
Function calling in action: Stack

eip

```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = ∗(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + ∗(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp - 0x18
  movl  $0, -4(%ebp)         ∗(ebp-4)=0
  movl  $41, (%esp)          ∗(esp) = 41
  movl  $42, 4(%esp)         ∗(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```



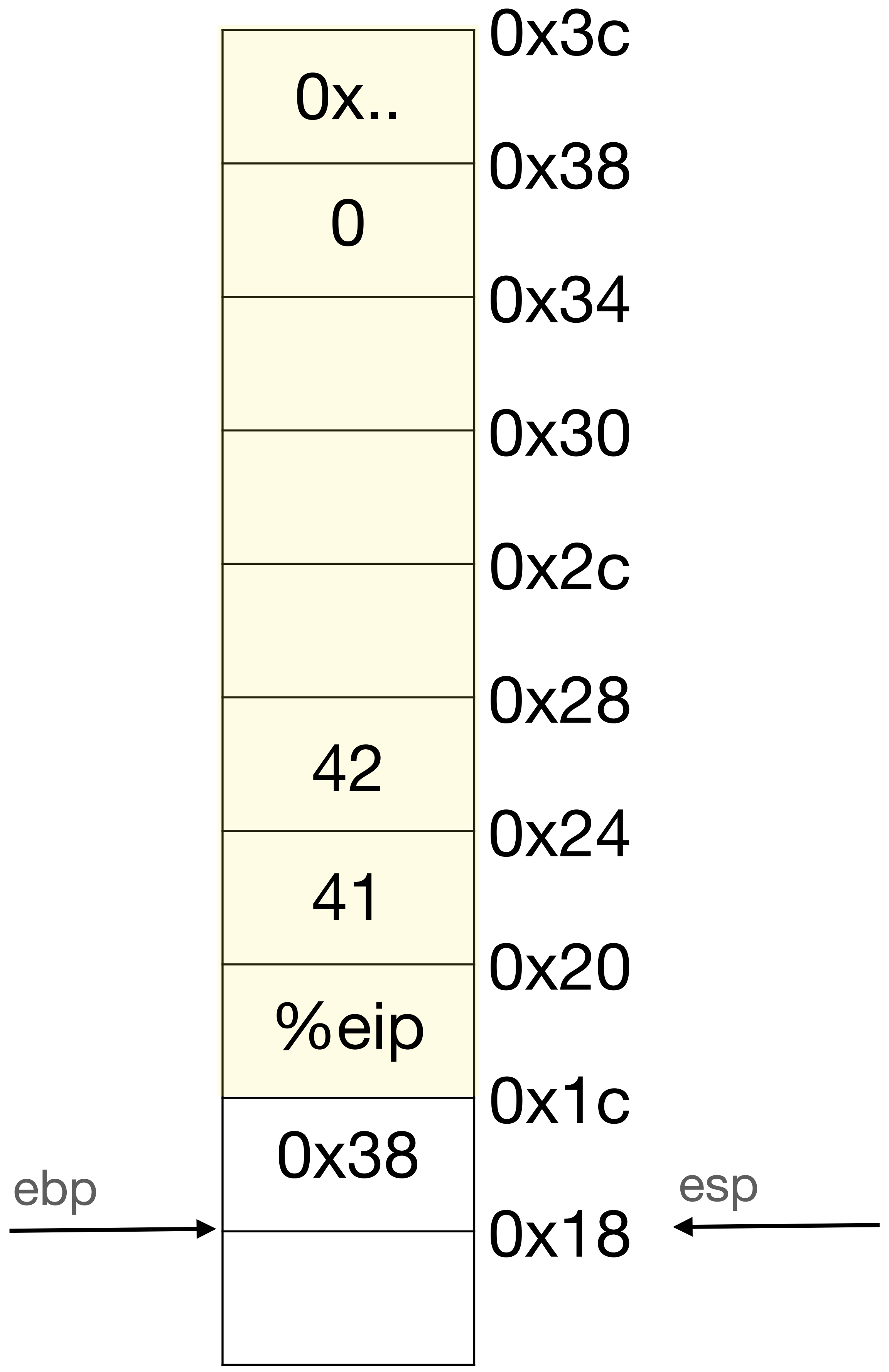
Function calling in action: Stack

02.s

eip

```
_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = ∗(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + ∗(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                            ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp − 0x18
  movl  $0, −4(%ebp)         ∗(ebp−4)=0
  movl  $41, (%esp)          ∗(esp) = 41
  movl  $42, 4(%esp)         ∗(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```

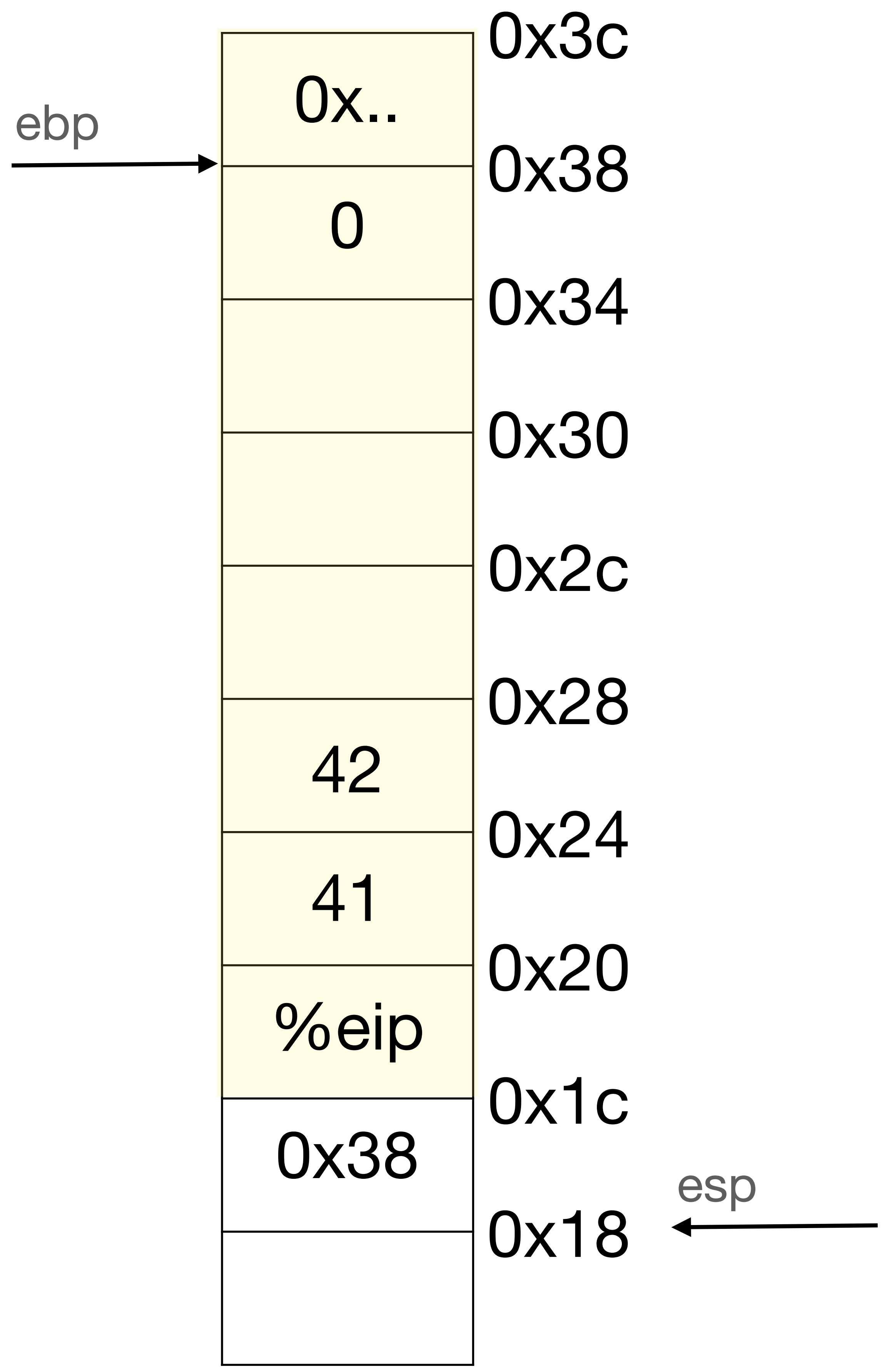


Function calling in action: Stack

```
02.s

_foo:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
eip → popl  %ebp              Restore caller’s base pointer
  retl                        change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  subl  $24, %esp             esp = esp - 0x18
  movl  $0, -4(%ebp)          *(ebp-4)=0
  movl  $41, (%esp)           *(esp) = 41
  movl  $42, 4(%esp)          *(esp+4) = 42
  calll _foo                  Push current eip on to stack, jump to foo
  addl  $24, %esp             esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                  Restore caller’s ebp
  retl
```



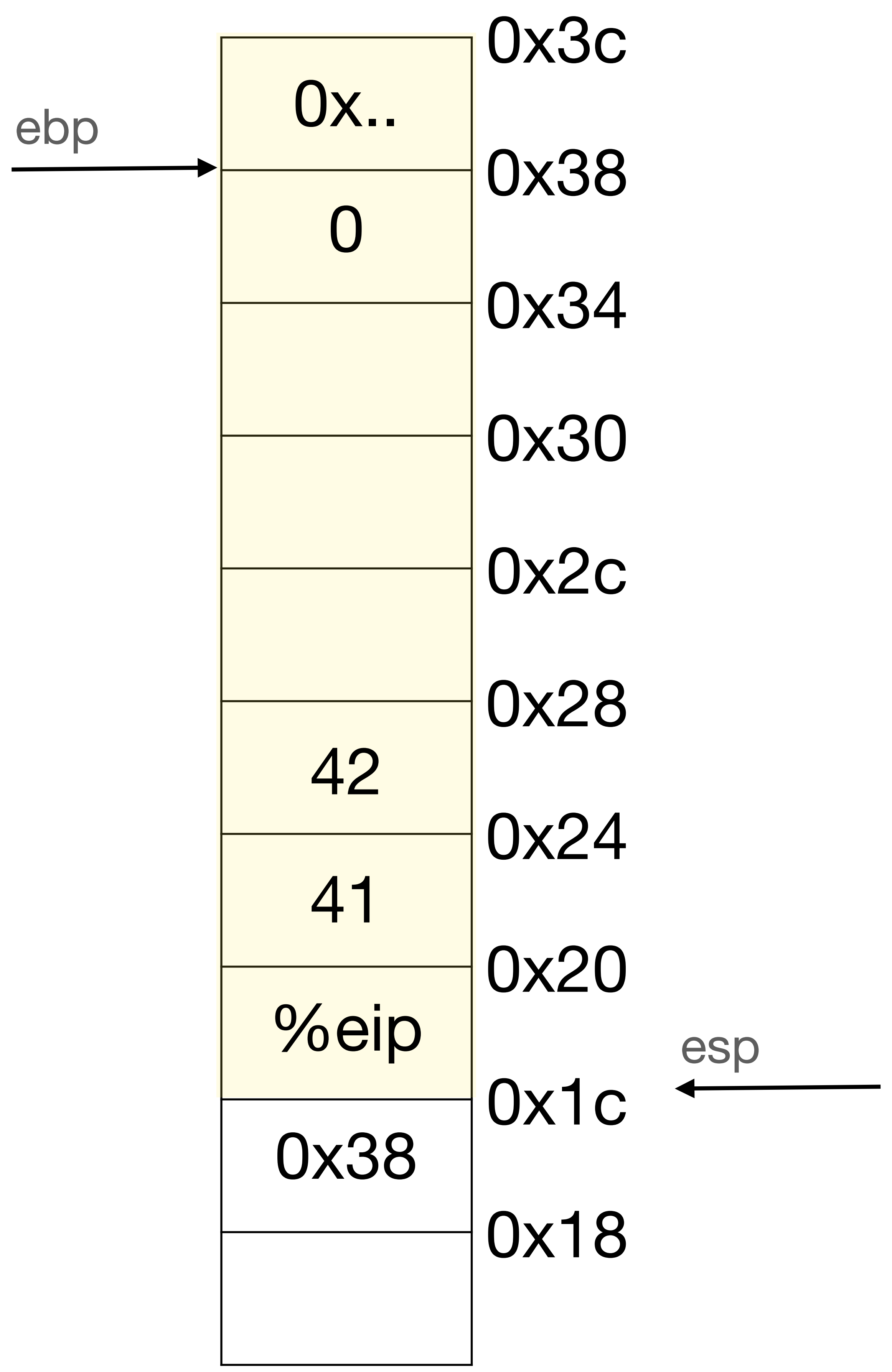
Function calling in action: Stack

eip

```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = *(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + *(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp - 0x18
  movl  $0, -4(%ebp)         *(ebp-4)=0
  movl  $41, (%esp)          *(esp) = 41
  movl  $42, 4(%esp)         *(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```



Function calling in action: Stack

```
02.s

_foo:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
  popl  %ebp                  Restore caller’s base pointer
  retl                        change eip to return address

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  .p2align  4, 0x90
_main:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  subl  $24, %esp             esp = esp - 0x18
  movl  $0, -4(%ebp)          *(ebp-4)=0
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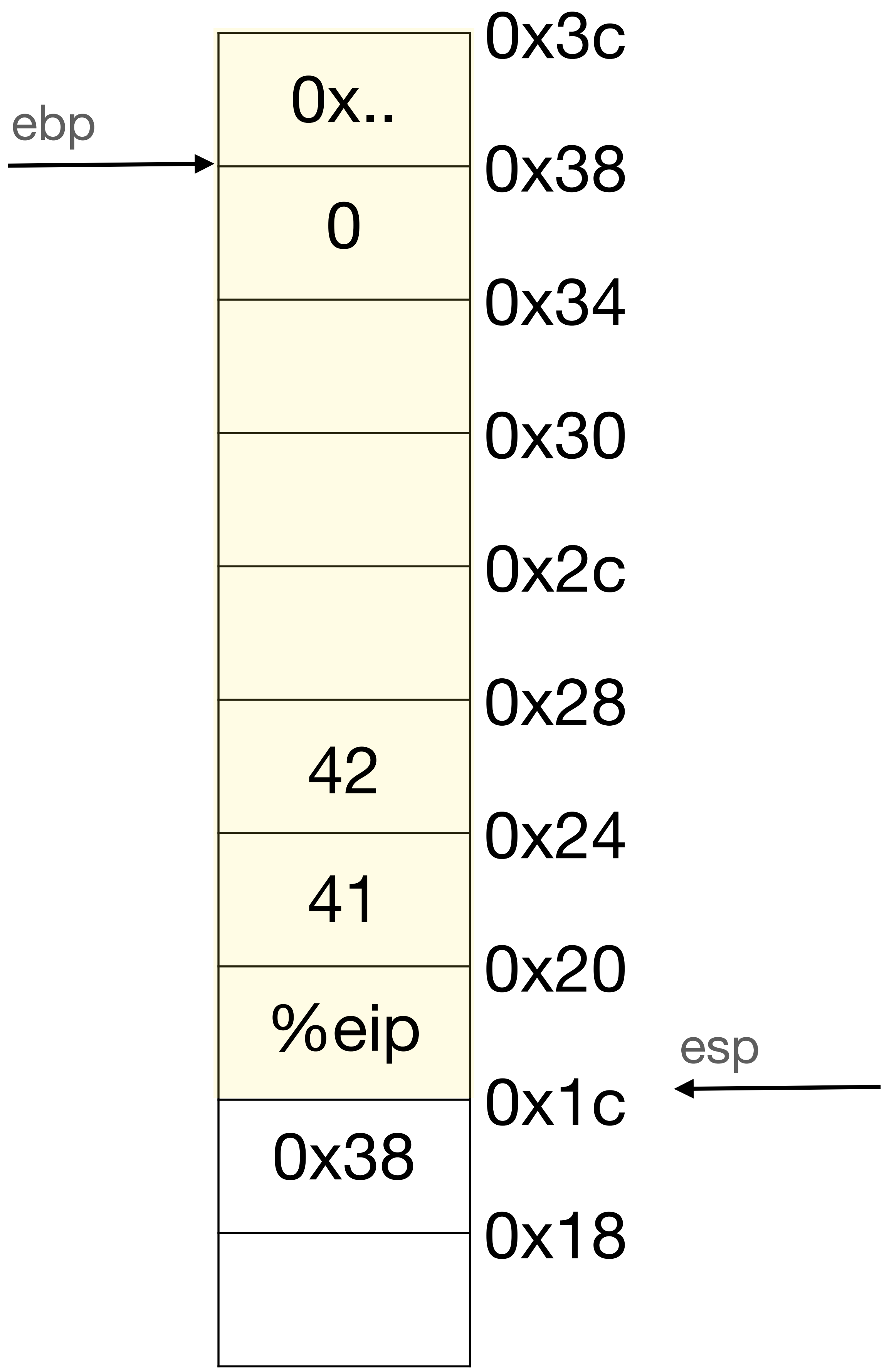
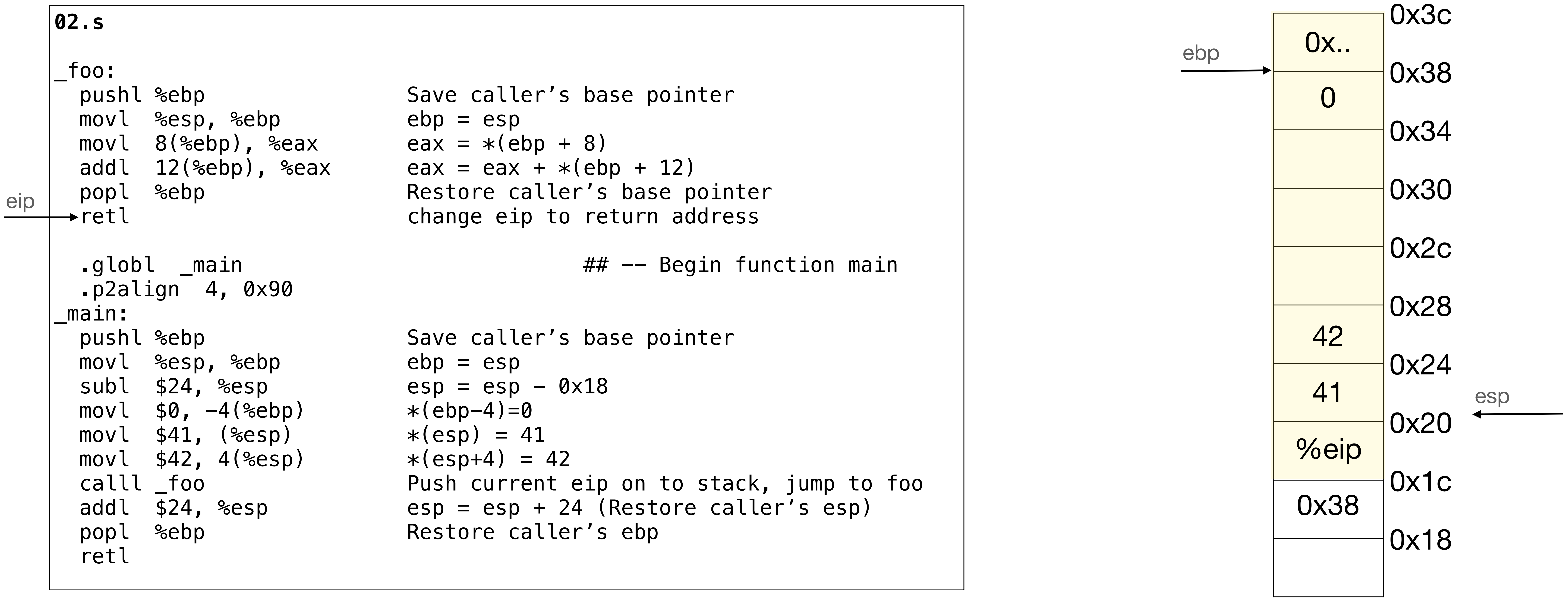
  calll _foo                  Push current eip on to stack, jump to foo
  addl  $24, %esp             esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                  Restore caller’s ebp
  retl
```

eip



Function calling in action: Stack



02.s

```
_foo:
  pushl %ebp                  Save caller's base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
  popl  %ebp                  Restore caller's base pointer
  retl                        change eip to return address

  .globl  _main                              ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                  Save caller's base pointer
  movl  %esp, %ebp            ebp = esp
  subl  $24, %esp             esp = esp - 0x18
  movl  $0, -4(%ebp)          *(ebp-4)=0
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  movl  $42, 4(%esp)          *(esp+4) = 42
  calll _foo                  Push current eip on to stack, jump to foo
  addl  $24, %esp             esp = esp + 24 (Restore caller's esp)
  popl  %ebp                  Restore caller's ebp
  retl
```

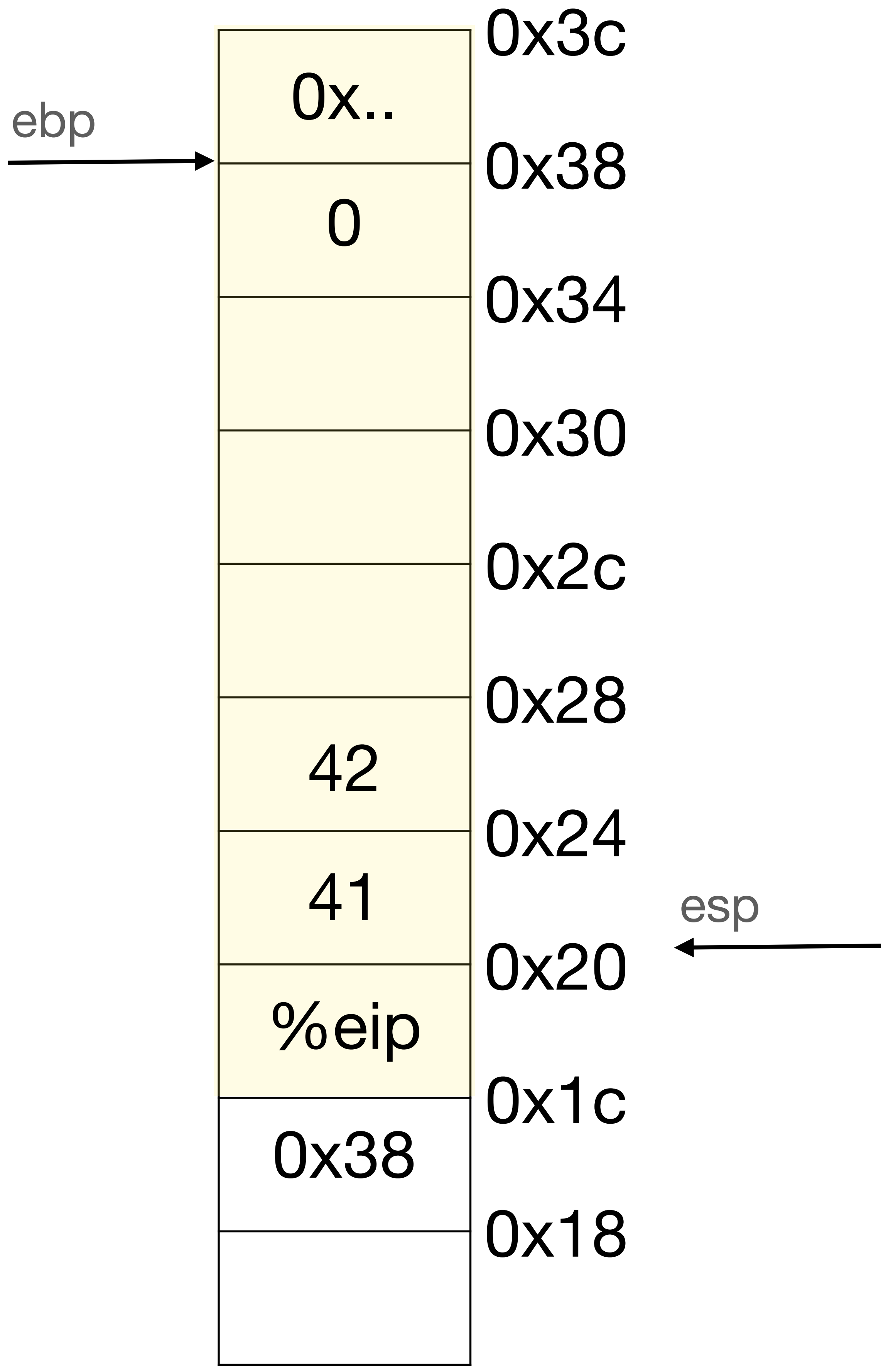
Function calling in action: Stack

02.s

```
_foo:
  pushl %ebp                Save caller’s base pointer
  movl  %esp, %ebp          ebp = esp
  movl  8(%ebp), %eax       eax = *(ebp + 8)
  addl  12(%ebp), %eax      eax = eax + *(ebp + 12)
  popl  %ebp                Restore caller’s base pointer
  retl                      change eip to return address

  .globl  _main                           ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                Save caller’s base pointer
  movl  %esp, %ebp          ebp = esp
  subl  $24, %esp           esp = esp - 0x18
  movl  $0, -4(%ebp)        *(ebp-4)=0
  movl  $41, (%esp)         *(esp) = 41
  movl  $42, 4(%esp)        *(esp+4) = 42
  calll _foo                Push current eip on to stack, jump to foo
  addl  $24, %esp           esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                Restore caller’s ebp
  retl
```

eip → addl $24, %esp

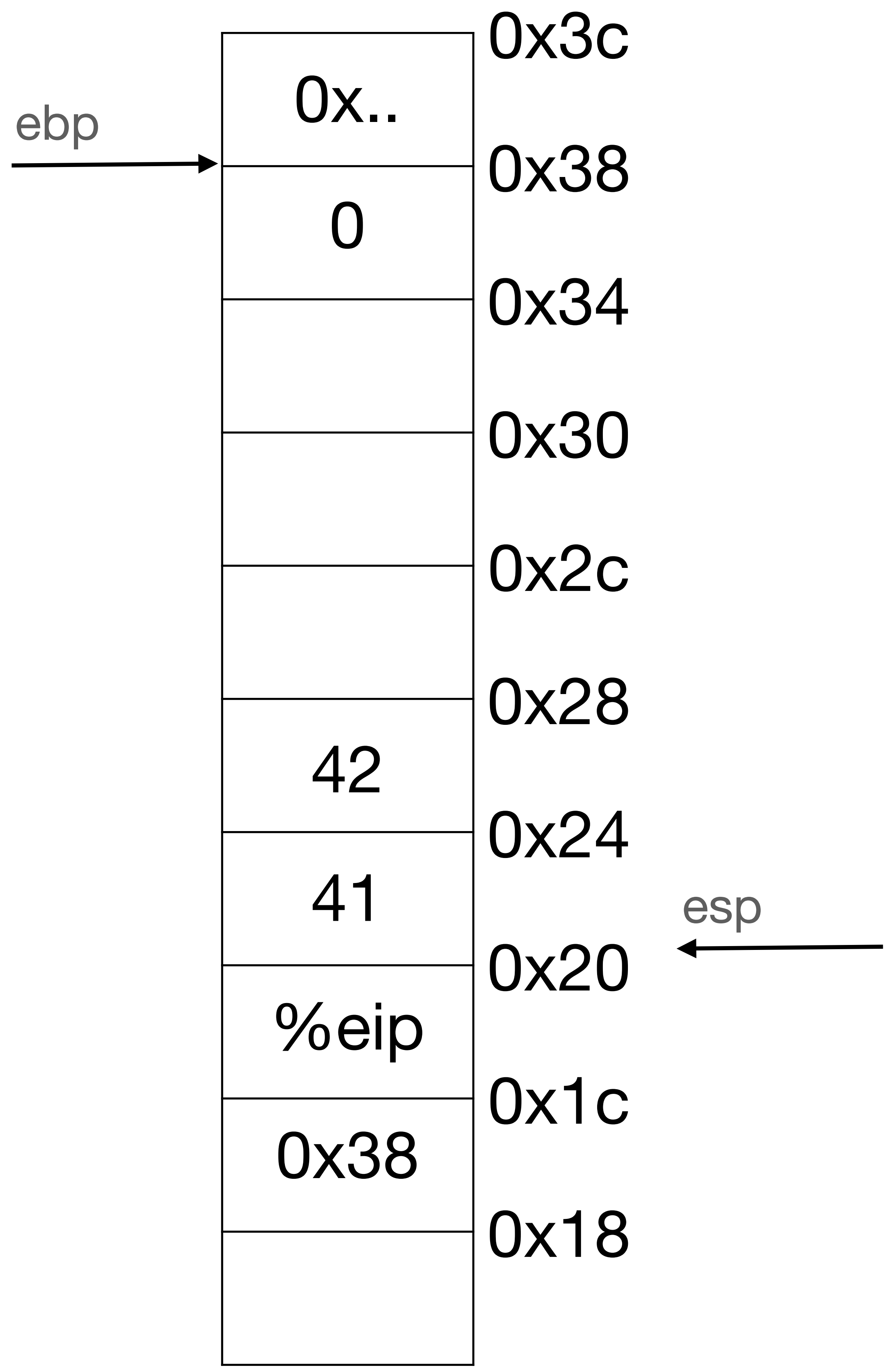


Function calling in action: Stack

```
02.s

_foo:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  movl  8(%ebp), %eax         eax = *(ebp + 8)
  addl  12(%ebp), %eax        eax = eax + *(ebp + 12)
  popl  %ebp                  Restore caller’s base pointer
  retl                        change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                  Save caller’s base pointer
  movl  %esp, %ebp            ebp = esp
  subl  $24, %esp             esp = esp - 0x18
  movl  $0, -4(%ebp)          *(ebp-4)=0
  movl  $41, (%esp)           *(esp) = 41
  movl  $42, 4(%esp)          *(esp+4) = 42
  calll _foo                  Push current eip on to stack, jump to foo
eip → addl  $24, %esp         esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                  Restore caller’s ebp
  retl
```



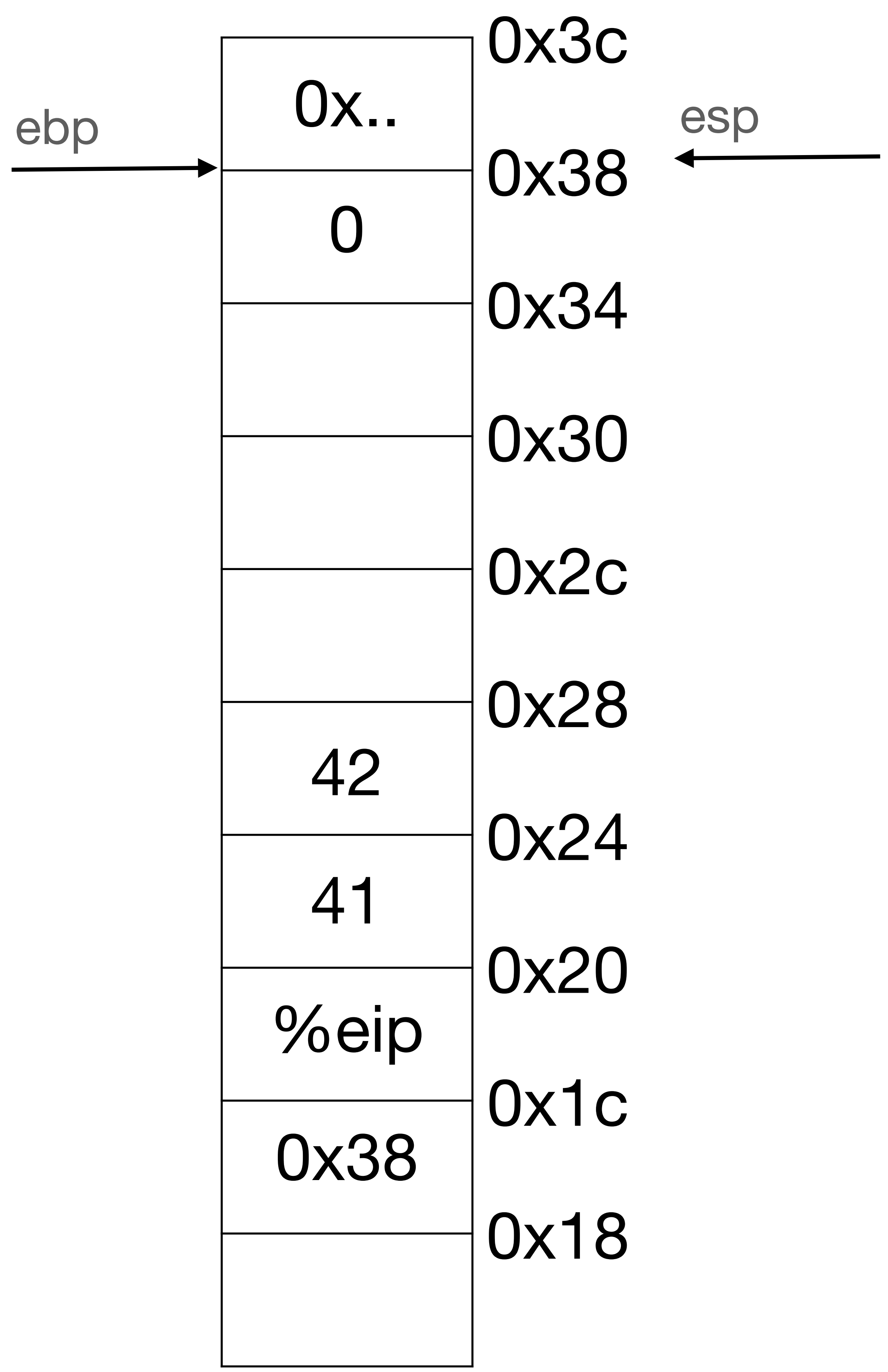
Function calling in action: Stack

```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = *(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + *(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp - 0x18
  movl  $0, -4(%ebp)         *(ebp-4)=0
  movl  $41, (%esp)          *(esp) = 41
  movl  $42, 4(%esp)         *(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
  retl
```

eip



Function calling in action: Stack

```
02.s

_foo:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  movl  8(%ebp), %eax        eax = *(ebp + 8)
  addl  12(%ebp), %eax       eax = eax + *(ebp + 12)
  popl  %ebp                 Restore caller’s base pointer
  retl                       change eip to return address

  .globl  _main                             ## -- Begin function main
  .p2align  4, 0x90
_main:
  pushl %ebp                 Save caller’s base pointer
  movl  %esp, %ebp           ebp = esp
  subl  $24, %esp            esp = esp - 0x18
  movl  $0, -4(%ebp)         *(ebp-4)=0
  movl  $41, (%esp)          *(esp) = 41
  movl  $42, 4(%esp)         *(esp+4) = 42
  calll _foo                 Push current eip on to stack, jump to foo
  addl  $24, %esp            esp = esp + 24 (Restore caller’s esp)
  popl  %ebp                 Restore caller’s ebp
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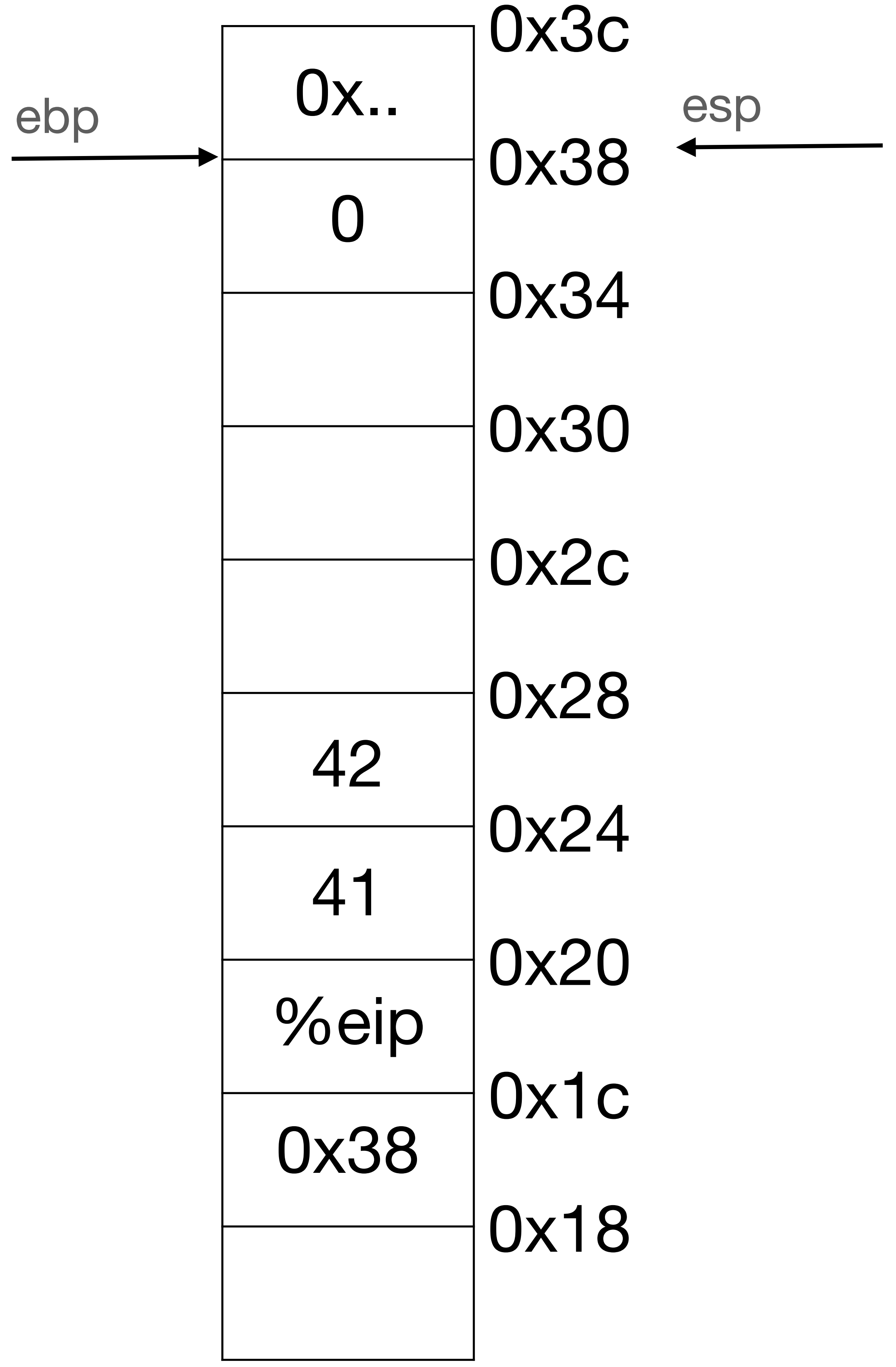
```

eip



Function calling in action: Stack

```
02.s

_foo:
  pushl %ebp                Save caller’s base pointer
  movl  %esp, %ebp          ebp = esp
  movl  8(%ebp), %eax       eax = ∗(ebp + 8)
  addl  12(%ebp), %eax      eax = eax + ∗(ebp + 12)
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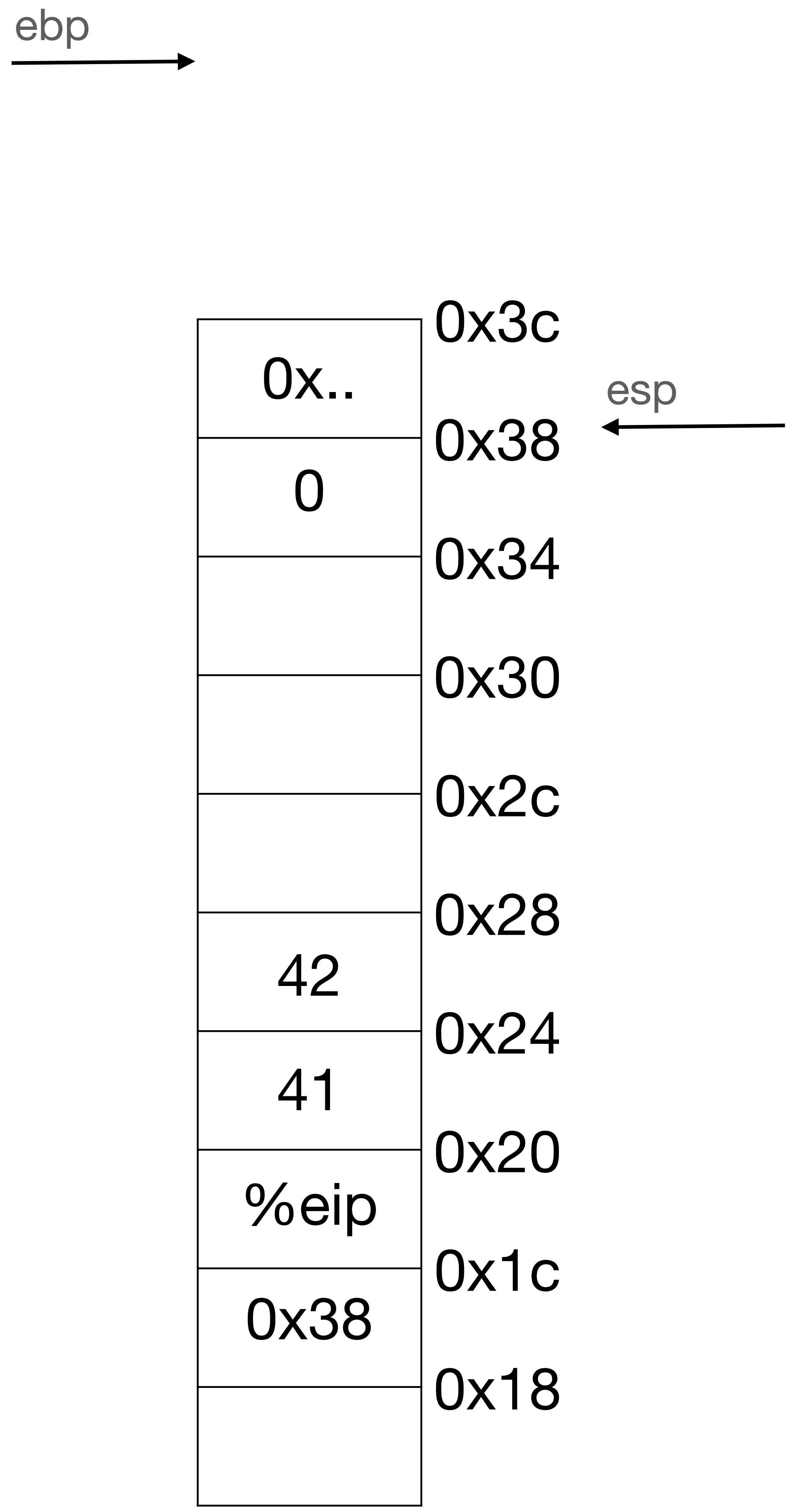
eip



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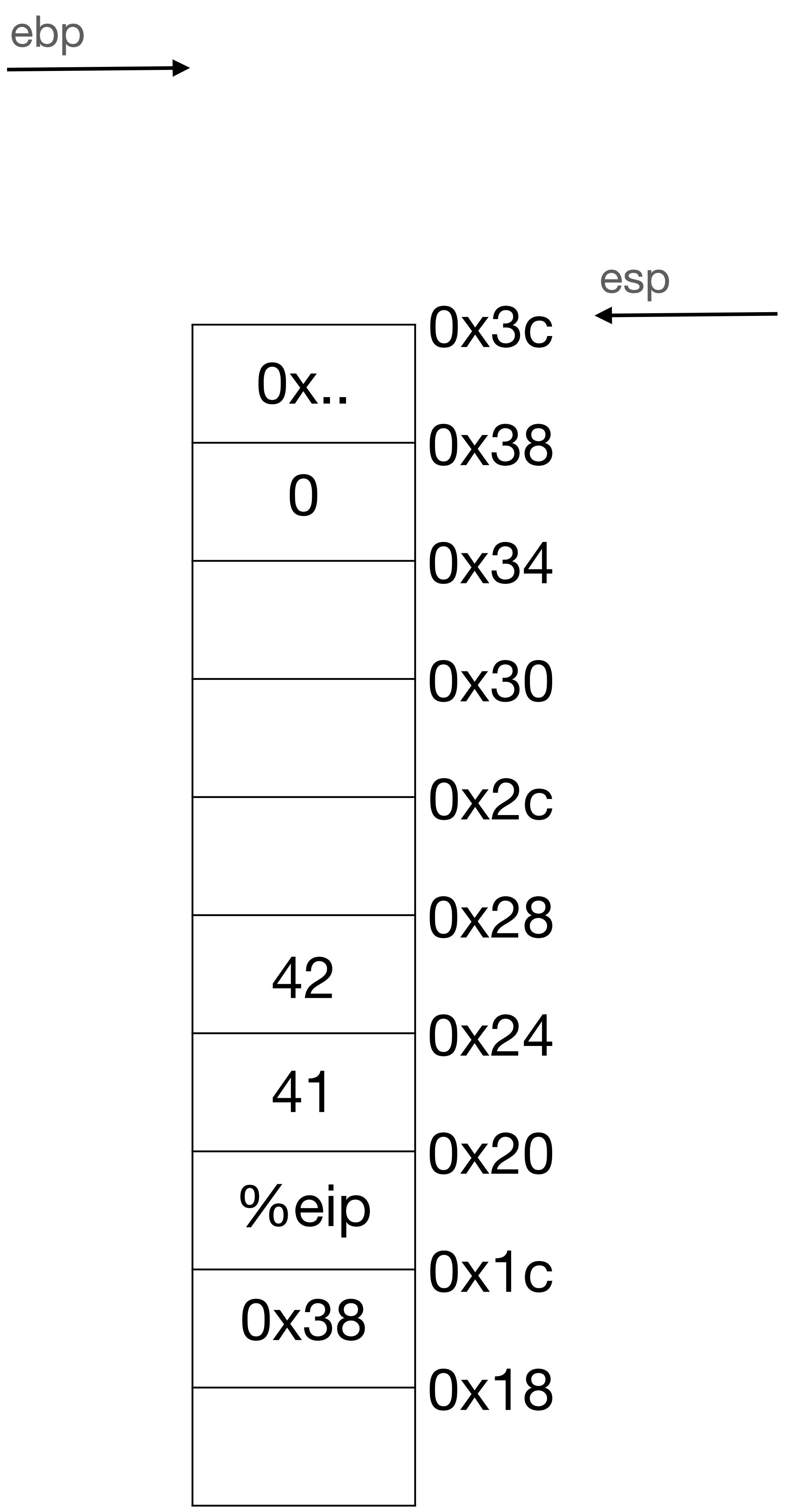
```

eip →



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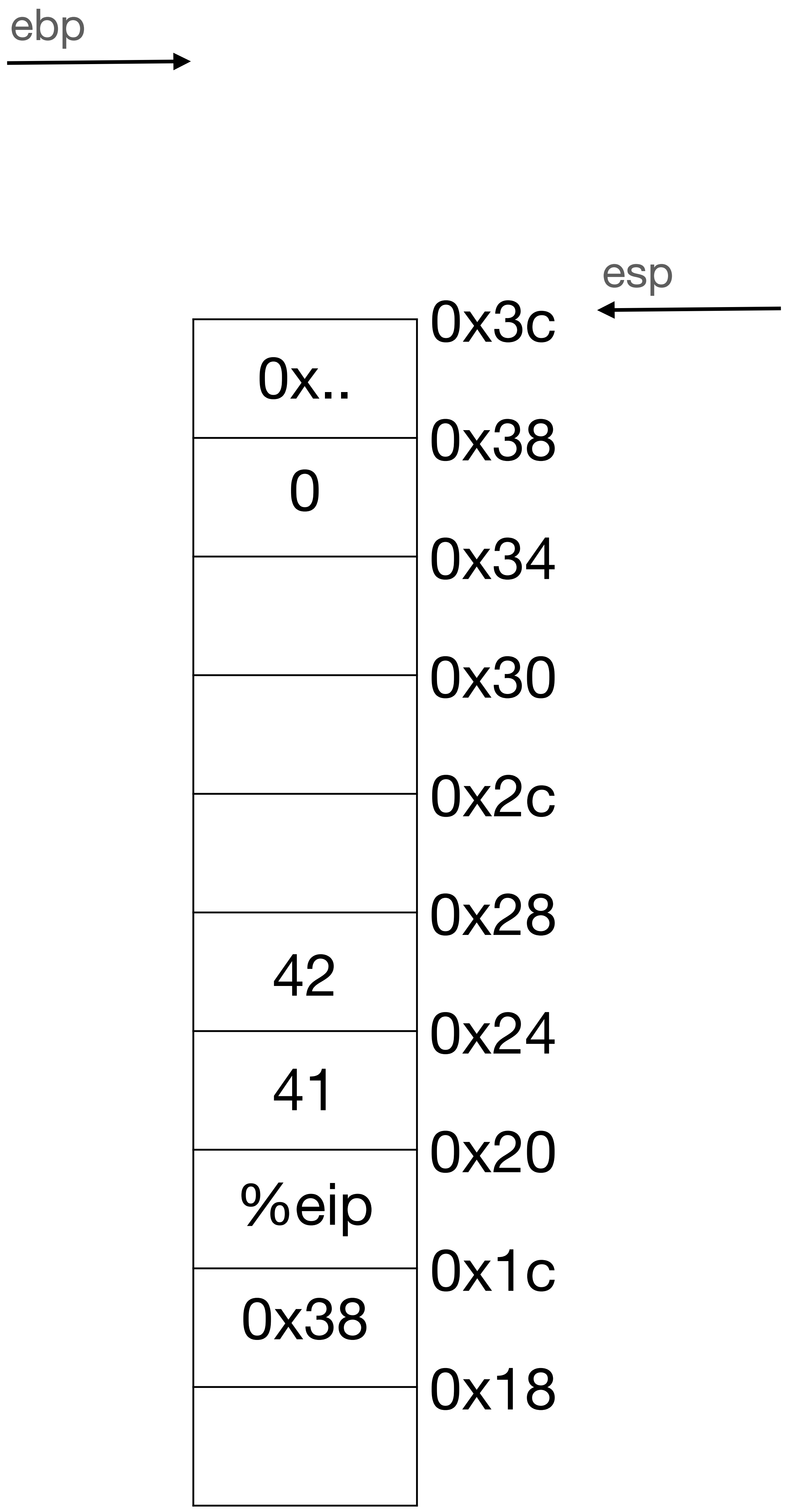

gcc calling convention

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at entry to a function (i.e. just after call):

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after ret instruction:

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gcc calling convention

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called function may have trashed arguments

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called function may have trashed arguments

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- %eip points at first instruction of function
- %esp points at return address
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- %eip contains return address
- %esp points at arguments pushed by caller

called function may have trashed arguments

- %eax contains return value (or trash if function is void)
- %eax, %edx, and %ecx may be trashed (caller save)
- %ebp, %ebx, %esi, %edi must contain contents from time of call (callee save)

Instructions are in memory!

02.s

```
_foo:
  pushl %ebp
  movl  %esp, %ebp
  movl  8(%ebp), %eax
  addl  12(%ebp), %eax
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  movl  %esp, %ebp
  subl  $24, %esp
  movl  $0, -4(%ebp)
  movl  $41, (%esp)
  movl  $42, 4(%esp)
  calll _foo
  addl  $24, %esp
  popl  %ebp
  retl
```

```
gcc -m32 -c 02.s -o 02.o
vim 02.o
:%!xxd
```

Instructions are in memory!

```
02.s

_foo:
  pushl %ebp
  movl  %esp, %ebp
  movl  8(%ebp), %eax
  addl  12(%ebp), %eax
  popl  %ebp
  retl

  .globl  _main
  .p2align  4, 0x90
_main:
  pushl %ebp
  movl  %esp, %ebp
  subl  $24, %esp
  movl  $0, -4(%ebp)
  movl  $41, (%esp)
  movl  $42, 4(%esp)
  calll _foo
  addl  $24, %esp
  popl  %ebp
  retl
```

```
gcc -m32 -c 02.s -o 02.o
objdump -d 02.o > 02.dump
```

call 0x0123	pushl %eip (*) movl $0x123, %eip (*)
ret	popl %eip (*)

```
00000000 <_foo>:
0: 55                          pushl  %ebp
1: 89 e5                       movl   %esp, %ebp
3: 8b 45 0c                    movl   12(%ebp), %eax
6: 8b 45 08                    movl   8(%ebp), %eax
9: 8b 45 08                    movl   8(%ebp), %eax
c: 03 45 0c                    addl   12(%ebp), %eax
f: 5d                          popl   %ebp
10: c3                         retl


00000020 <_main>:
20: 55                         pushl  %ebp
21: 89 e5                      movl   %esp, %ebp
23: 83 ec 18                   subl   $24, %esp
26: c7 45 fc 00 00 00 00       movl   $0, -4(%ebp)
2d: c7 04 24 29 00 00 00       movl   $41, (%esp)
34: c7 44 24 04 2a 00 00 00    movl   $42, 4(%esp)
3c: e8 bf ff ff ff             calll  0x0 <_foo>
41: 83 c4 18                   addl   $24, %esp
44: 5d                         popl   %ebp
45: c3                         retl
```

* fake instructions
call saves eip of next instruction

Instructions are in memory!

```
02.s

_foo:
  pushl %ebp
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41 = 0x 00 00 00 29

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41 = 0x 00 00 00 29

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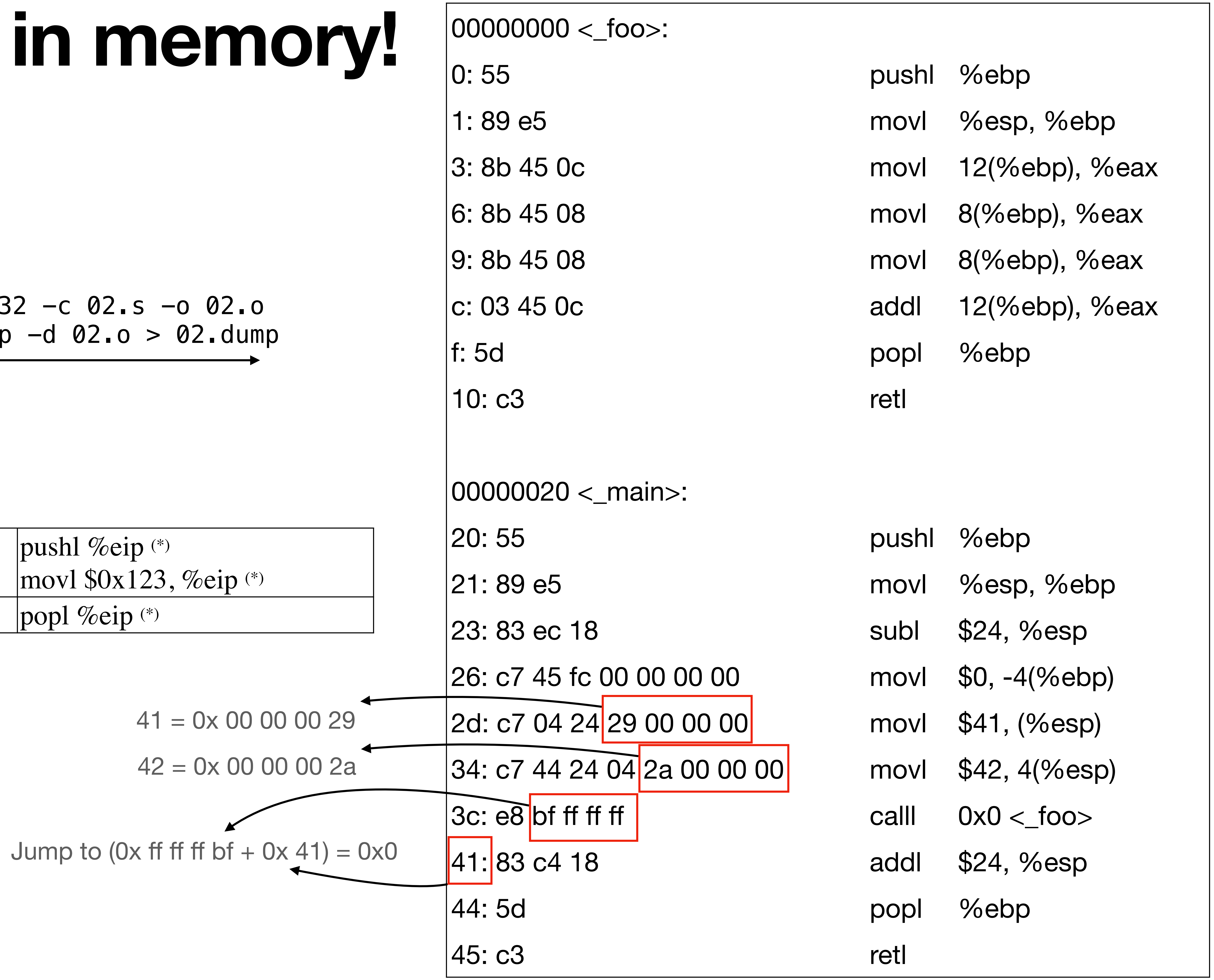

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41 = 0x 00 00 00 29

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Jump to (0x ff ff ff bf + 0x 41) = 0x0

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Compiling, linking, loading

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- *Linker* takes multiple *'.o's*, produces a single *program image a.out* (binary) *02.main.o, 02.func.o -> 02.main*

- *Loader* loads the program image into memory at run-time and starts executing it

Memory access hierarchy: caches

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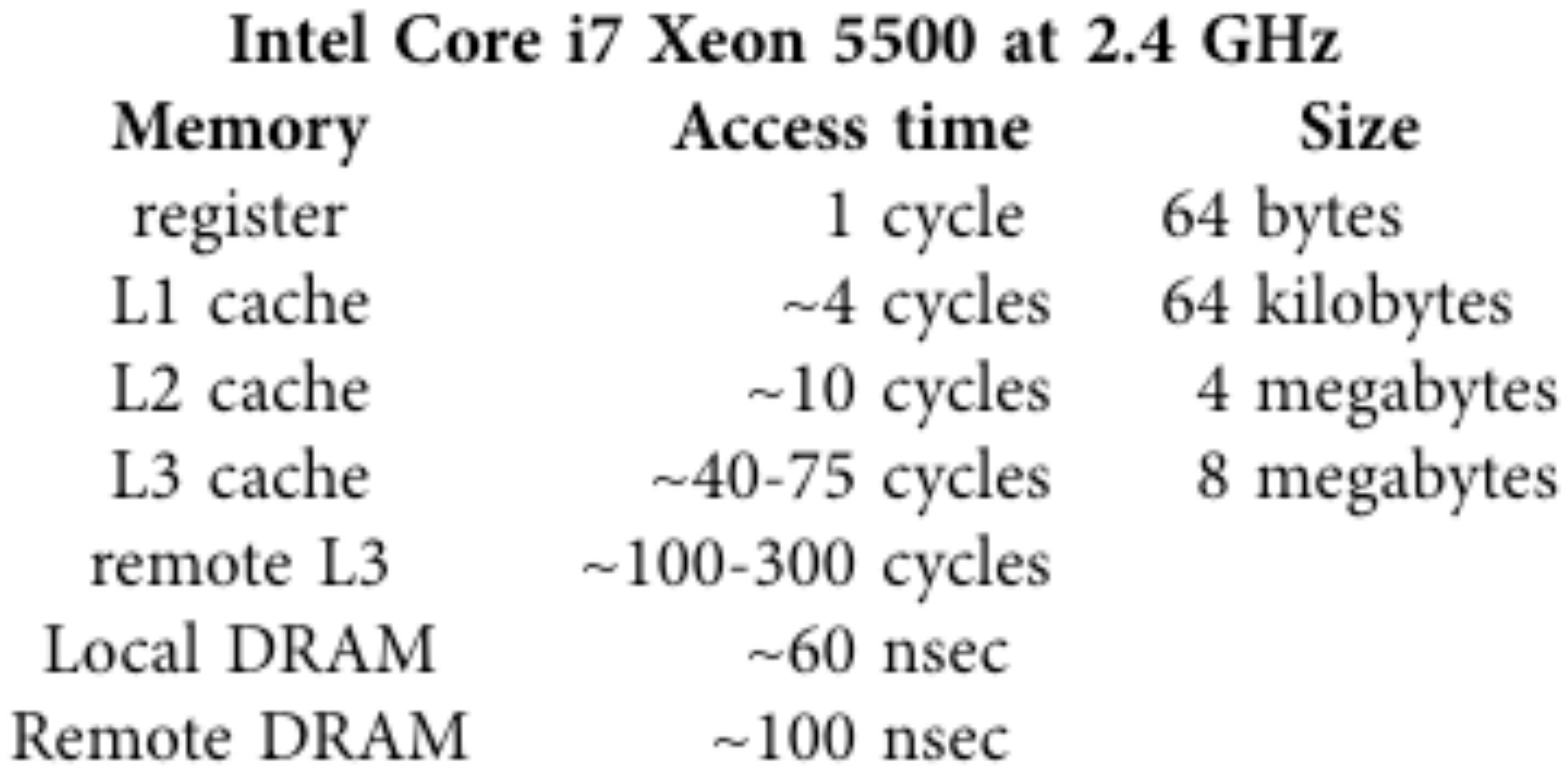

Intel Core i7 Xeon 5500 at 2.4 GHz

Memory	Access time	Size
register	1 cycle	64 bytes
L1 cache	~4 cycles	64 kilobytes
L2 cache	~10 cycles	4 megabytes
L3 cache	~40-75 cycles	8 megabytes
remote L3	~100-300 cycles	
Local DRAM	~60 nsec	
Remote DRAM	~100 nsec	

Figure A-1. Latency umbers for an Intel i7 Xeon system, based on http://software.intel.com /sites/products/collateral/hpc/vtune/performance_analysis_guide.pdf.

I/O devices

Port-mapped IO

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```

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Writing a byte to line printer

#define DATA_PORT    0x378
#define STATUS_PORT  0x379
```

I/O devices

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Writing a byte to line printer

#define DATA_PORT    0x378
#define STATUS_PORT  0x379
#define CONTROL_PORT 0x37A
```

I/O devices

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Writing a byte to line printer

#define DATA_PORT    0x378
#define STATUS_PORT  0x379
#define CONTROL_PORT 0x37A
#define   BUSY 0x80
```

I/O devices

Port-mapped IO

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Writing a byte to line printer

#define DATA_PORT    0x378
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#define CONTROL_PORT 0x37A
#define   BUSY 0x80
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```

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void
```

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void
lpt_putc(char c)
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#define   BUSY 0x80
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void
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  /* wait for printer to consume previous byte */
```

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void
lpt_putc(char c)
{
  /* wait for printer to consume previous byte */
  while((inb(STATUS_PORT) & BUSY) == 0);
```

I/O devices

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#define STATUS_PORT  0x379
#define CONTROL_PORT 0x37A
#define   BUSY 0x80
#define   STROBE 0x01
void
lpt_putc(char c)
{
  /* wait for printer to consume previous byte */
  while((inb(STATUS_PORT) & BUSY) == 0);
```

I/O devices

Port-mapped IO

- Similar to reading from (writing to) memory locations
- Special instructions:
  - inb (outb) reads (writes) a byte to port
- Only 1024 ports

Writing a byte to line printer

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  /* put the byte on the data lines */
  outb(DATA_PORT, c);

  /* tell the printer to look at the data */
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I/O devices

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I/O devices

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I/O devices

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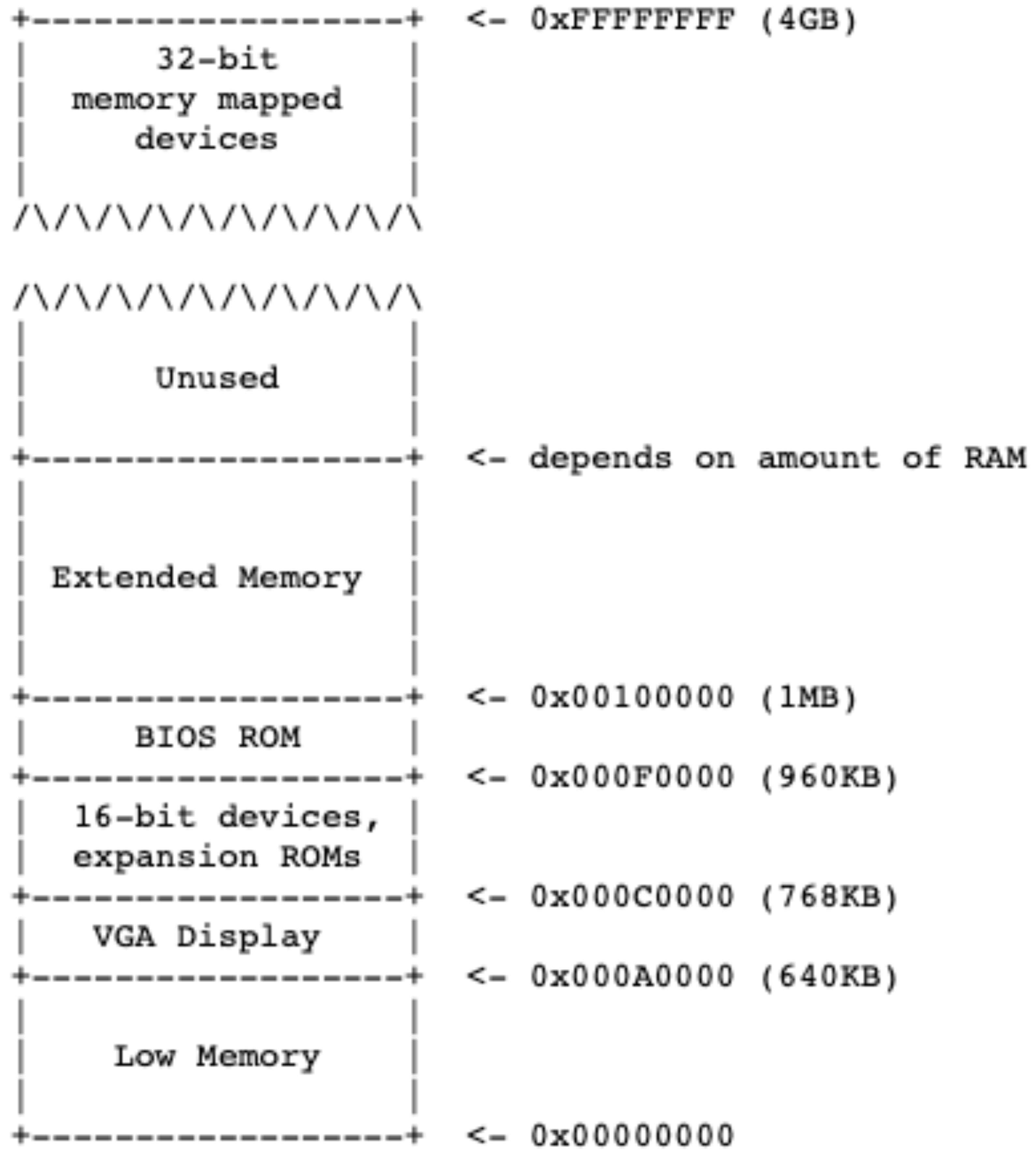
  /* put the byte on the data lines */
  outb(DATA_PORT, c);

  /* tell the printer to look at the data */
  outb(CONTROL_PORT, STROBE);
  outb(CONTROL_PORT, 0);
}
```

I/O devices

Memory-mapped IO



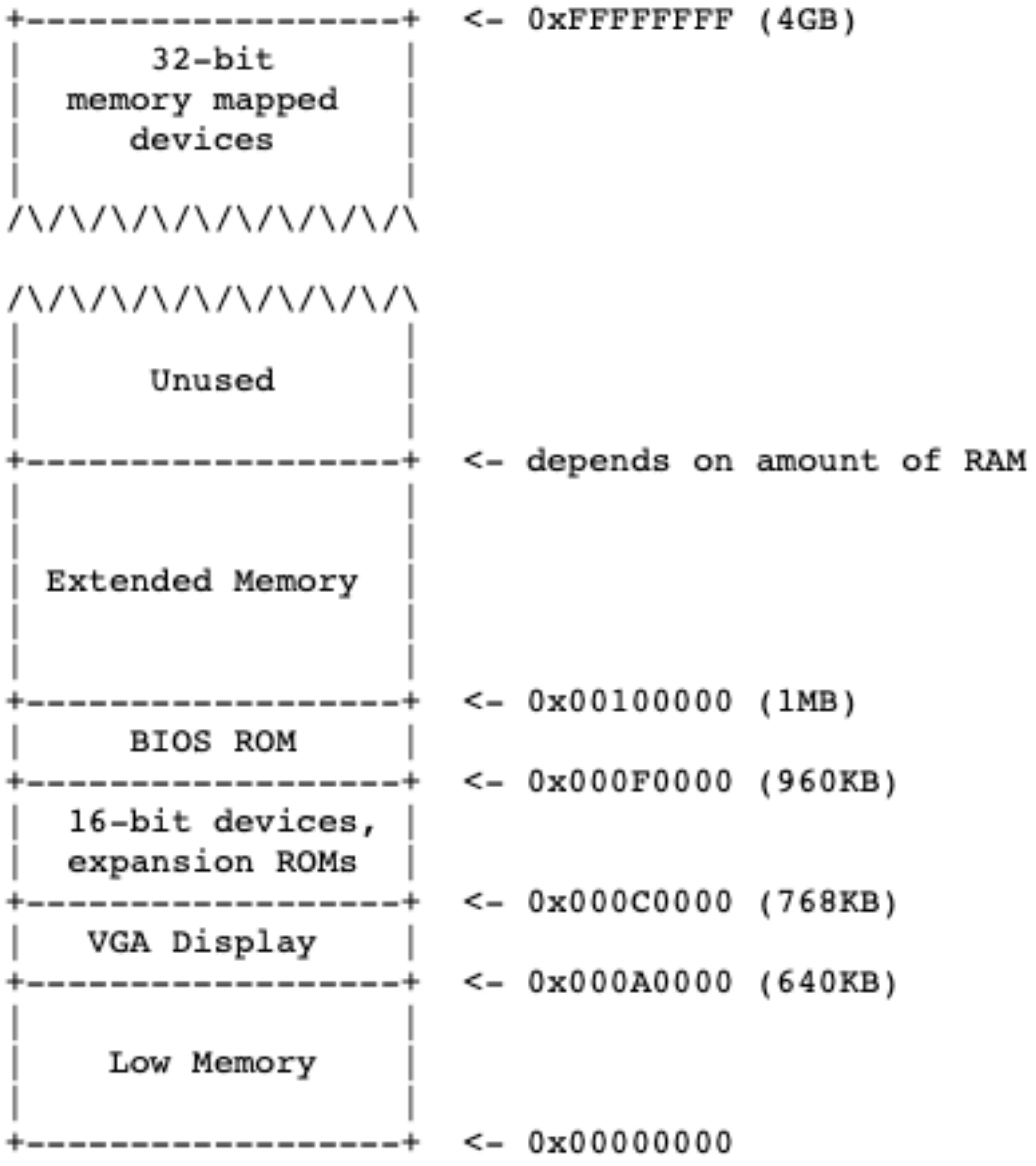
```
+------------------+  <- 0xFFFFFFFF (4GB)
|      32-bit      |
|  memory mapped   |
|     devices      |
|                  |
/\/\/\/\/\/\/\/\/\/\

/\/\/\/\/\/\/\/\/\/\
|                  |
|      Unused      |
|                  |
+------------------+  <- depends on amount of RAM
|                  |
|                  |
| Extended Memory  |
|                  |
|                  |
+------------------+  <- 0x00100000 (1MB)
|     BIOS ROM     |
+------------------+  <- 0x000F0000 (960KB)
|  16-bit devices, |
|  expansion ROMs  |
+------------------+  <- 0x000C0000 (768KB)
|   VGA Display    |
+------------------+  <- 0x000A0000 (640KB)
|                  |
|    Low Memory    |
|                  |
+------------------+  <- 0x00000000
```

I/O devices

Memory-mapped IO

- Regular memory access instructions



```
+------------------+  <- 0xFFFFFFFF (4GB)
|      32-bit      |
|  memory mapped   |
|     devices      |
|                  |
/\/\/\/\/\/\/\/\/\/\

/\/\/\/\/\/\/\/\/\/\
|                  |
|      Unused      |
|                  |
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|                  |
|                  |
| Extended Memory  |
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|                  |
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+------------------+  <- 0x000F0000 (960KB)
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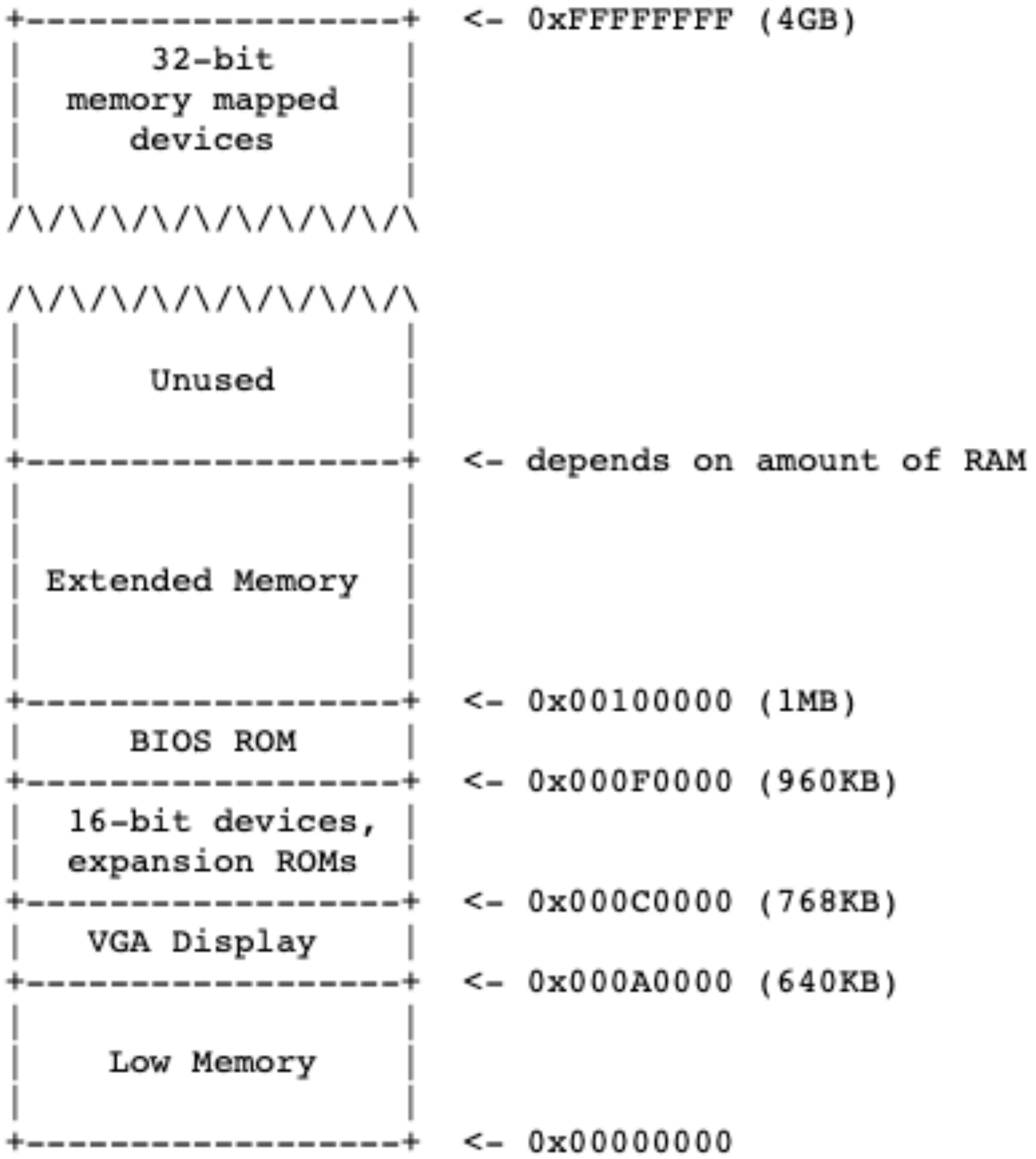
+------------------+  <- 0x000C0000 (768KB)
|   VGA Display    |
+------------------+  <- 0x000A0000 (640KB)
|                  |
|    Low Memory    |
|                  |
+------------------+  <- 0x00000000
```

I/O devices

Memory-mapped IO

- Regular memory access instructions
- Reads and writes are routed to appropriate device



```
+------------------+  <- 0xFFFFFFFF (4GB)
|      32-bit      |
|  memory mapped   |
|     devices      |
|                  |
/\/\/\/\/\/\/\/\/\/\

/\/\/\/\/\/\/\/\/\/\
|                  |
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|                  |
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+------------------+  <- 0x000C0000 (768KB)
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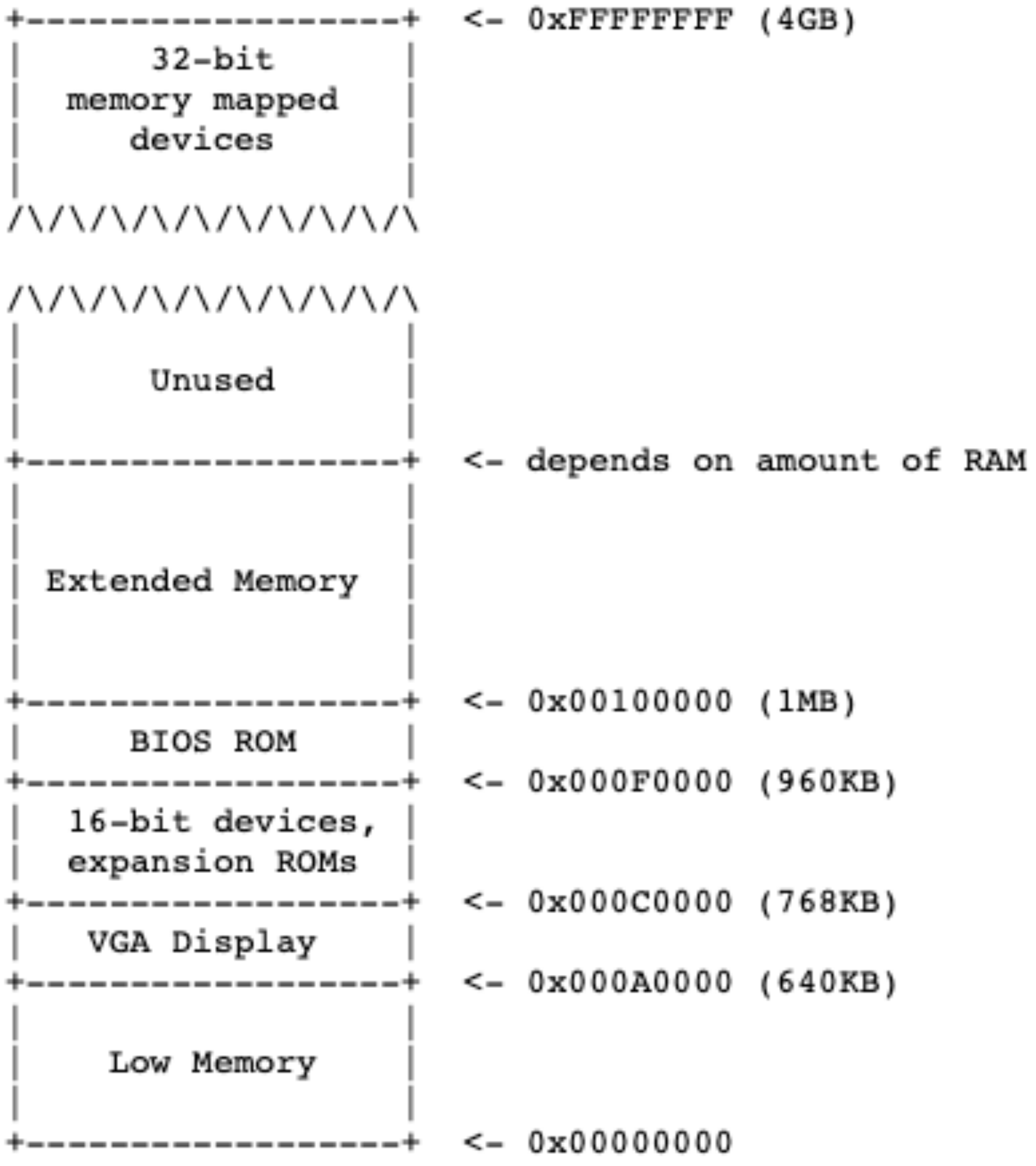
+------------------+  <- 0x000A0000 (640KB)
|                  |
|    Low Memory    |
|                  |
+------------------+  <- 0x00000000
```

I/O devices

Memory-mapped IO

- Regular memory access instructions
- Reads and writes are routed to appropriate device
    - Writes to VGA memory appear on the screen



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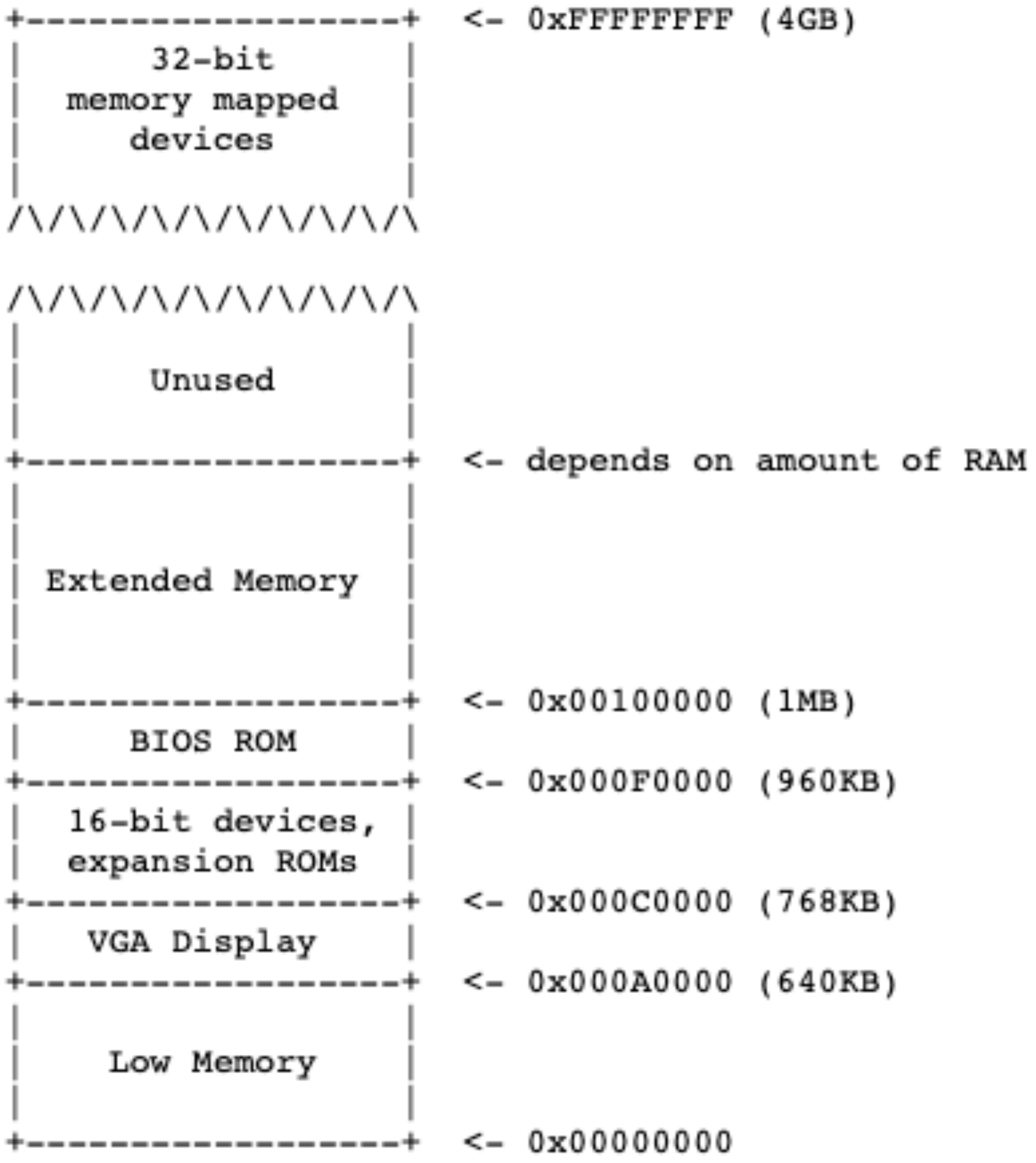
+------------------+  <- 0x000A0000 (640KB)
|                  |
|    Low Memory    |
|                  |
+------------------+  <- 0x00000000
```

I/O devices

Memory-mapped IO

- Regular memory access instructions
- Reads and writes are routed to appropriate device
  - Writes to VGA memory appear on the screen
- Power-on jumps %eip to 0x000F000



```
+------------------+  <- 0xFFFFFFFF (4GB)
|      32-bit      |
|  memory mapped   |
|     devices      |
|                  |
/\/\/\/\/\/\/\/\/\/\

/\/\/\/\/\/\/\/\/\/\
|                  |
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|                  |
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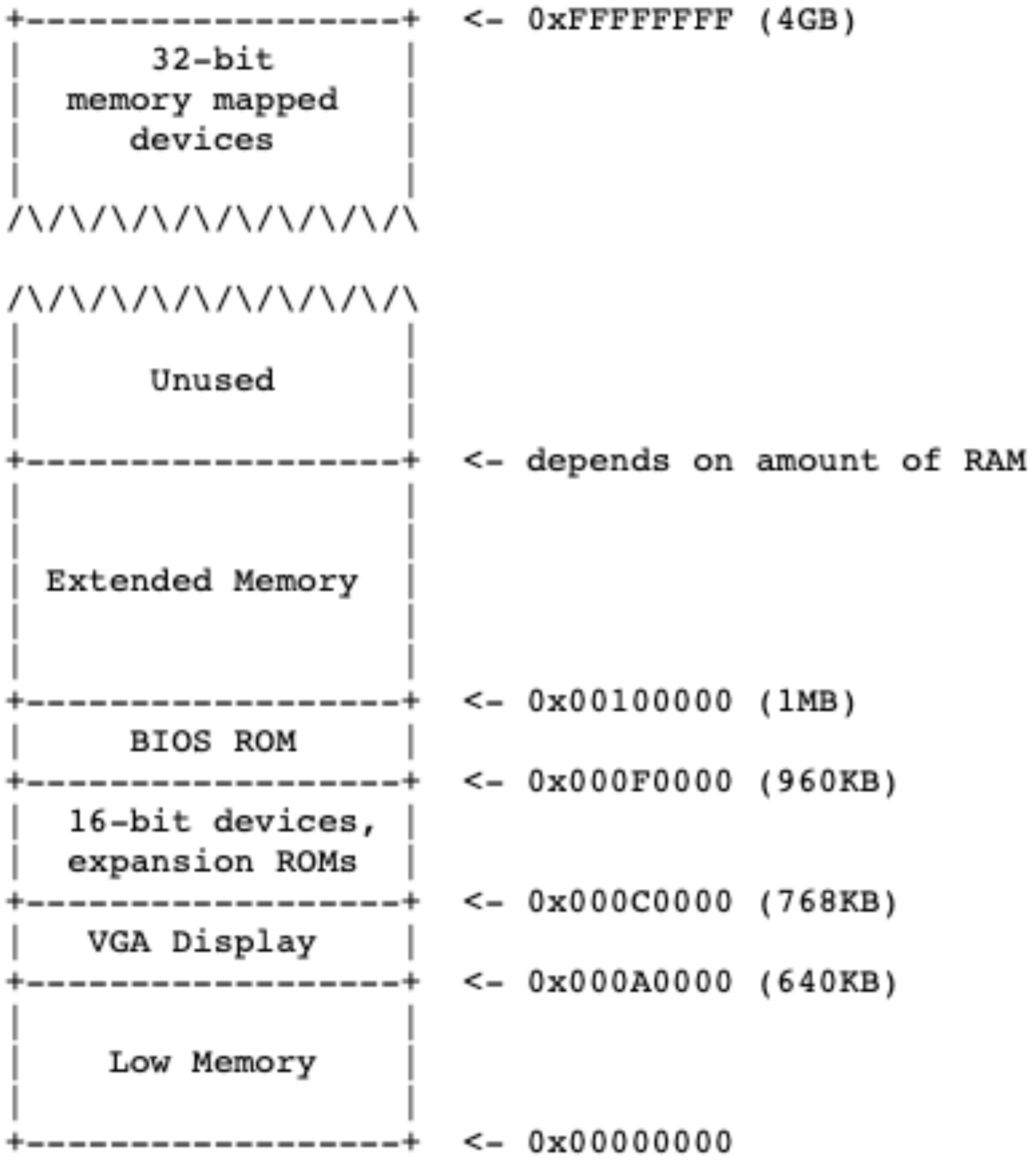
+------------------+  <- 0x00000000
```

I/O devices

Memory-mapped IO

- Regular memory access instructions
- Reads and writes are routed to appropriate device
  - Writes to VGA memory appear on the screen
- Power-on jumps %eip to 0x000F000
- Careful! Does not behave like memory!



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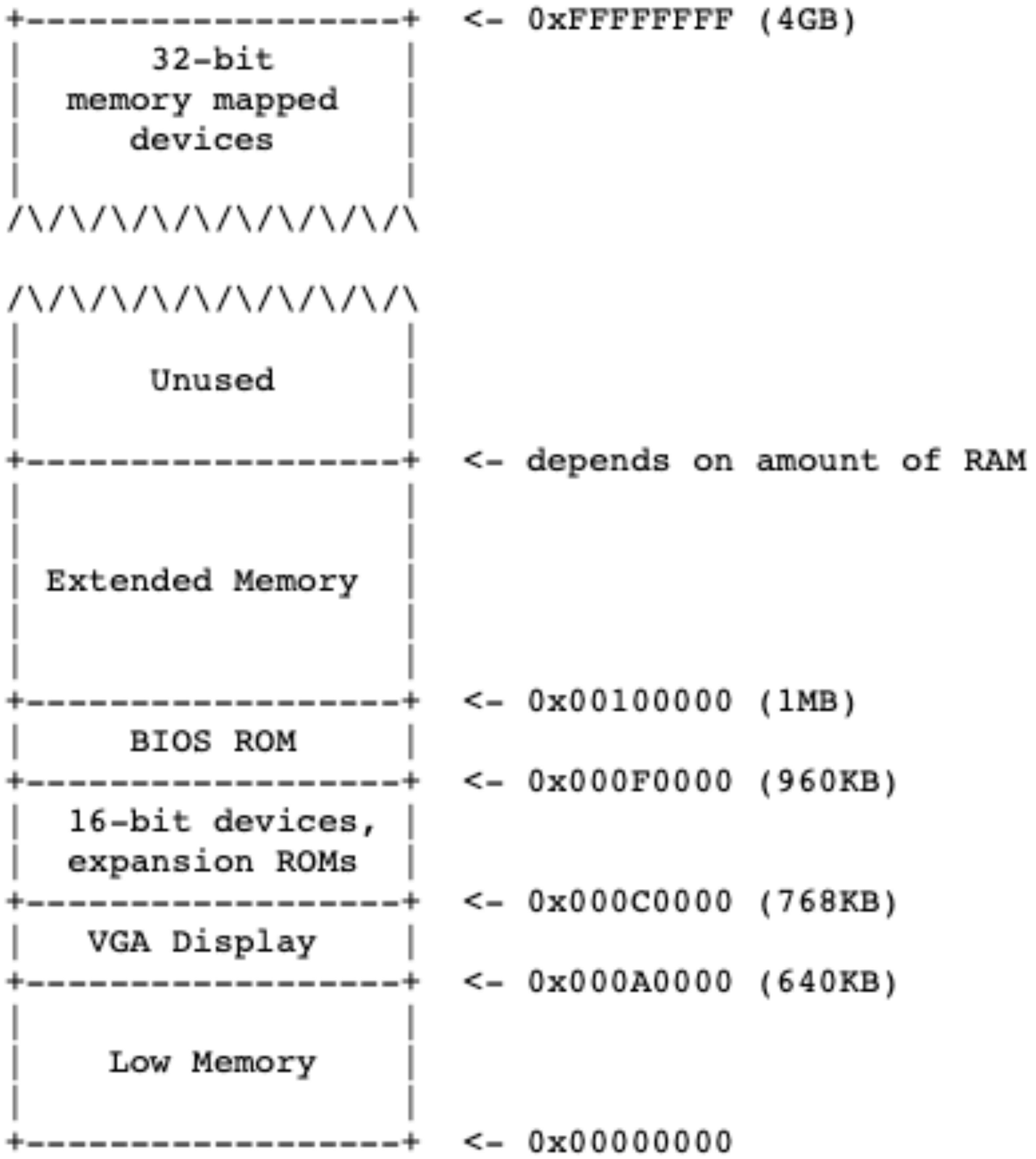
|                  |
|    Low Memory    |
|                  |
+------------------+  <- 0x00000000
```

I/O devices

Memory-mapped IO

- Regular memory access instructions
- Reads and writes are routed to appropriate device
    - Writes to VGA memory appear on the screen
- Power-on jumps %eip to 0x000F000
- Careful! Does not behave like memory!
    - Reading same location twice can change due to external events



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/\/\/\/\/\/\/\/\/\/\

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