

x86 and PC architecture

PC architecture

x86 instruction set

gcc calling convention

Agenda

Agenda

- Build a mental model of how PC components (e.g., CPU and memory) interact with one another

Agenda

- Build a mental model of how PC components (e.g., CPU and memory) interact with one another
- x86 instruction set: Defined by Intel in early 1980s. Has become a standard. Understand x86 instruction set so that we can read and write x86 assembly

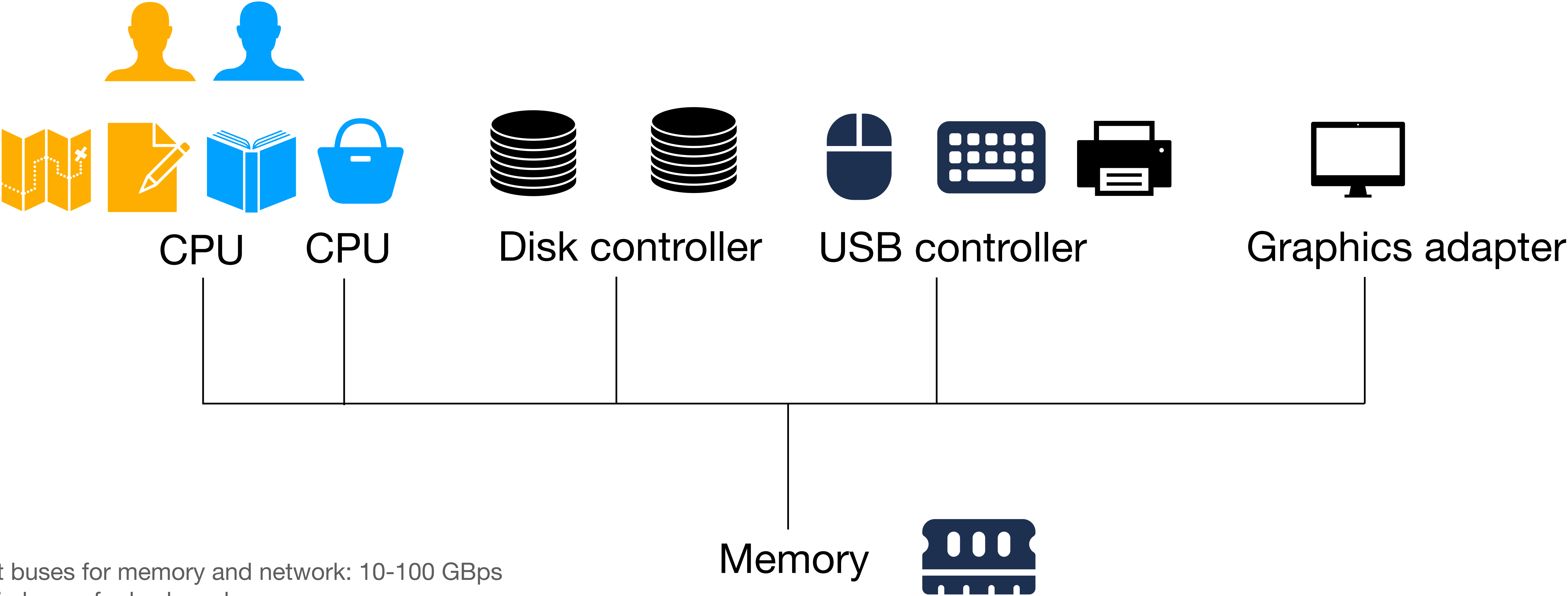
Agenda

- Build a mental model of how PC components (e.g., CPU and memory) interact with one another
- x86 instruction set: Defined by Intel in early 1980s. Has become a standard. Understand x86 instruction set so that we can read and write x86 assembly
 - Assembly programs are sometimes required by OS to get fine-grained control of the hardware

Agenda

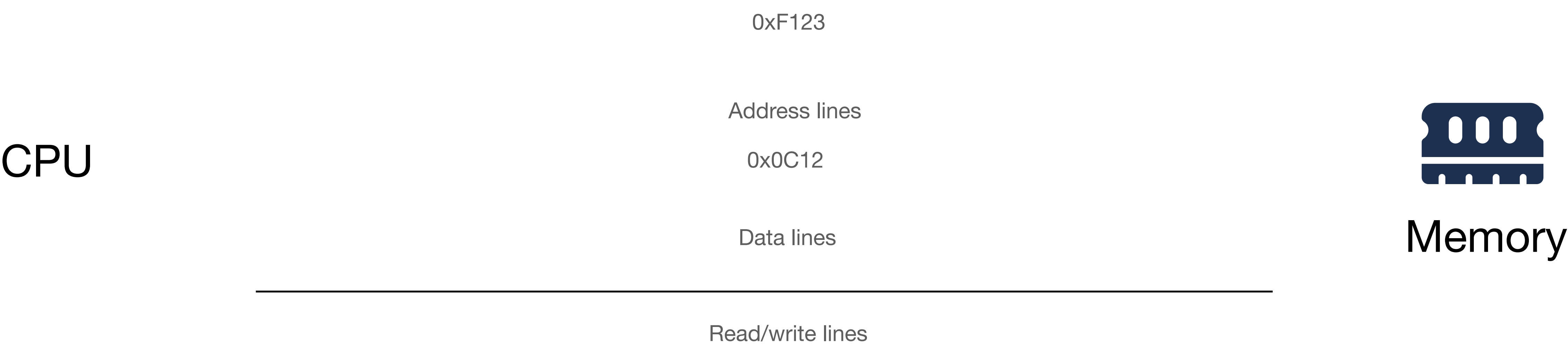
- Build a mental model of how PC components (e.g., CPU and memory) interact with one another
- x86 instruction set: Defined by Intel in early 1980s. Has become a standard. Understand x86 instruction set so that we can read and write x86 assembly
 - Assembly programs are sometimes required by OS to get fine-grained control of the hardware
- Understand gcc calling convention so that we can call C programs from assembly and vice-versa

Computer organization

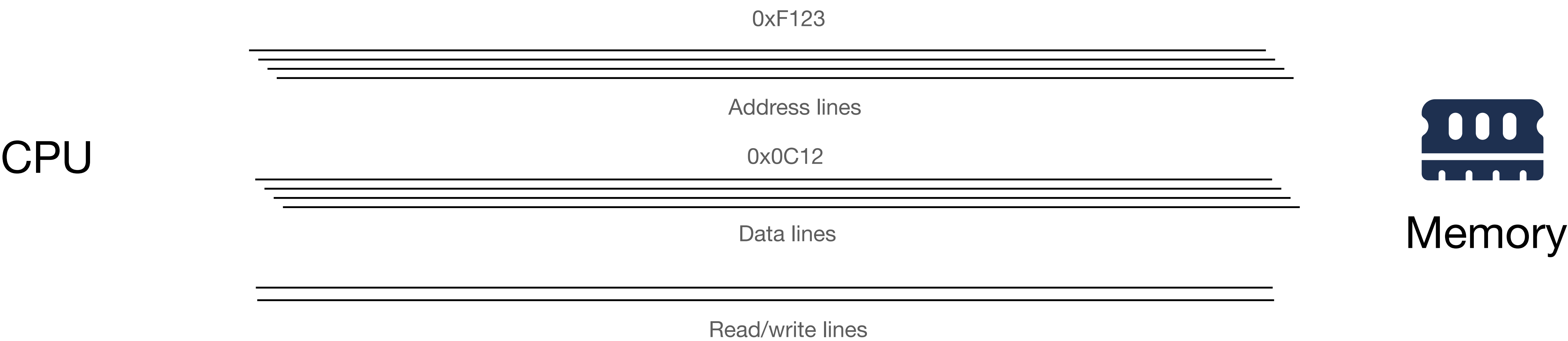


Fat buses for memory and network: 10-100 GBps
Thin buses for keyboard, mouse

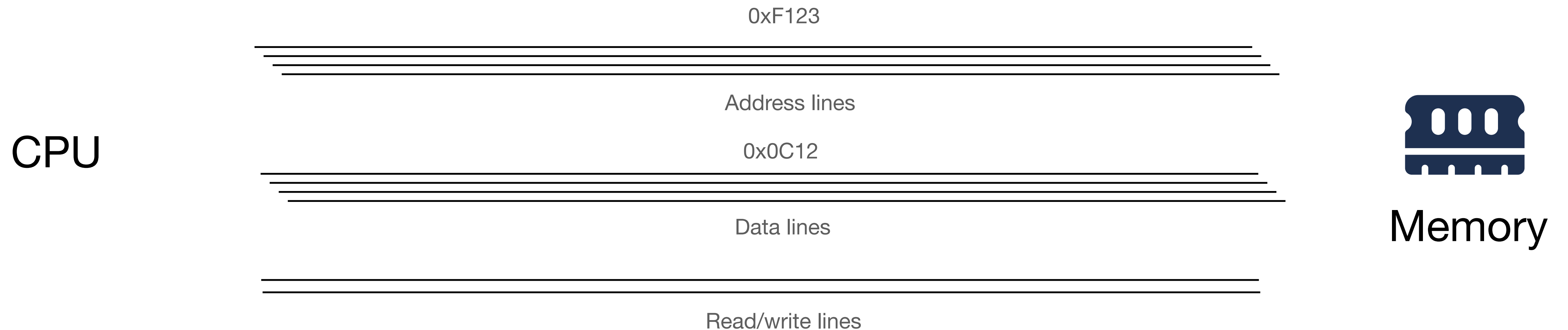
CPU-memory interaction



CPU-memory interaction

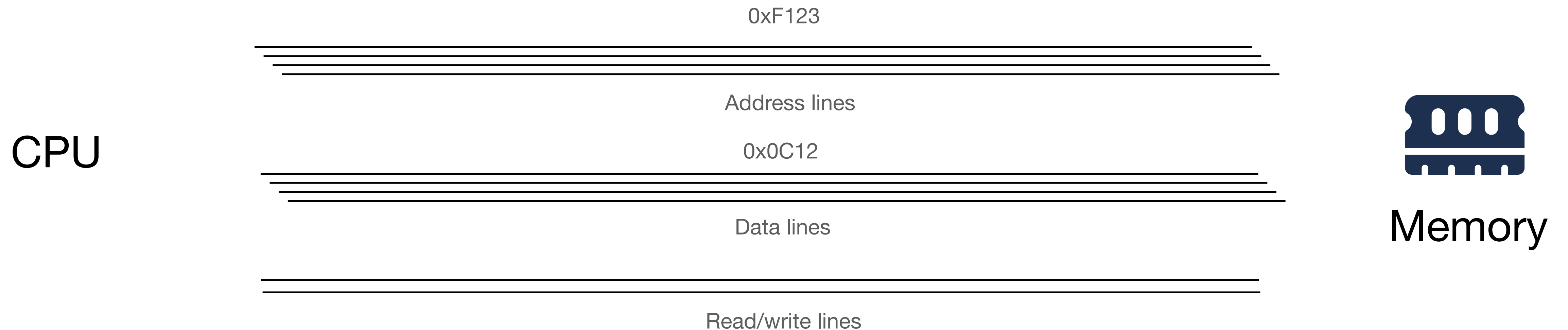


CPU-memory interaction



- Each read/write takes ~100 cycles

CPU-memory interaction



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

Registers

Registers

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

Registers

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

Registers

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

Registers

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

Registers

- **General purpose registers.**
 - **%eax, %ebx, %ecx, %edx**
 - **%edi: destination index, %esi: source index**
- Flags register. %eflags
- Instruction pointer. %eip
- Stack registers. %ebp: base pointer, %esp: stack pointer
- Special registers.
 - Control registers %cr0, %cr2, %cr3, %cr4;
 - Segment registers %cs, %ds, %es, %fs, %gs, %ss
 - Global and local descriptor table registers %gdtr, %ldtr

Registers

- **General purpose registers.**
 - **%eax, %ebx, %ecx, %edx**
 - **%edi: destination index, %esi: source index**
- Flags register. %eflags
- Instruction pointer. %eip
- Stack registers. %ebp: base pointer, %esp: stack pointer
- Special registers.
 - Control registers %cr0, %cr2, %cr3, %cr4;
 - Segment registers %cs, %ds, %es, %fs, %gs, %ss
 - Global and local descriptor table registers %gdtr, %ldtr
- Other registers not used in xv6: 8 80-bit floating point registers, debug registers

mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent
----------	----------------

mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent
movl %eax, %edx	edx = eax

mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent
movl %eax, %edx	edx = eax
movl \$123, %edx	edx=0x123

mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent
movl %eax, %edx	edx = eax
movl \$123, %edx	edx=0x123
movl 0x123, %edx	%edx = *(int32_t*)0x123

mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent
movl %eax, %edx	edx = eax
movl \$123, %edx	edx=0x123
movl 0x123, %edx	%edx = *(int32_t*)0x123
movl (%ebx), %edx	edx=*(int32_t*) ebx

mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent
movl %eax, %edx	edx = eax
<u>movl \$123, %edx</u>	<u>edx=0x123</u>
movl 0x123, %edx	%edx = *(int32_t*)0x123
movl (%ebx), %edx	edx=*(int32_t*) ebx
movl 4(%ebx), %edx	edx=*(int32_t*)(ebx+4)

mov instructions

Intel SDM Vol 1 7.3.1.1

Assembly	“C” equivalent
movl %eax, %edx	edx = eax
movl \$123, %edx	edx=0x123
movl 0x123, %edx	%edx = *(int32_t*)0x123
movl (%ebx), %edx	edx=*(int32_t*) ebx
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	
			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

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

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

Figure 3-5. Alternate General-Purpose Register Names

Other instruction variants

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

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`
- Stack registers. `%ebp`: base pointer, `%esp`: stack pointer
- Special registers.
 - Control registers `%cr0`, `%cr2`, `%cr3`, `%cr4`;
 - Segment registers `%cs`, `%ds`, `%es`, `%fs`, `%gs`, `%ss`
 - Global and local descriptor table registers `%gdtr`, `%ldtr`
- Other registers not used in xv6: 8 80-bit floating point registers, debug registers

EFLAGS

- Carry flag: Most significant bit overflowed.

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

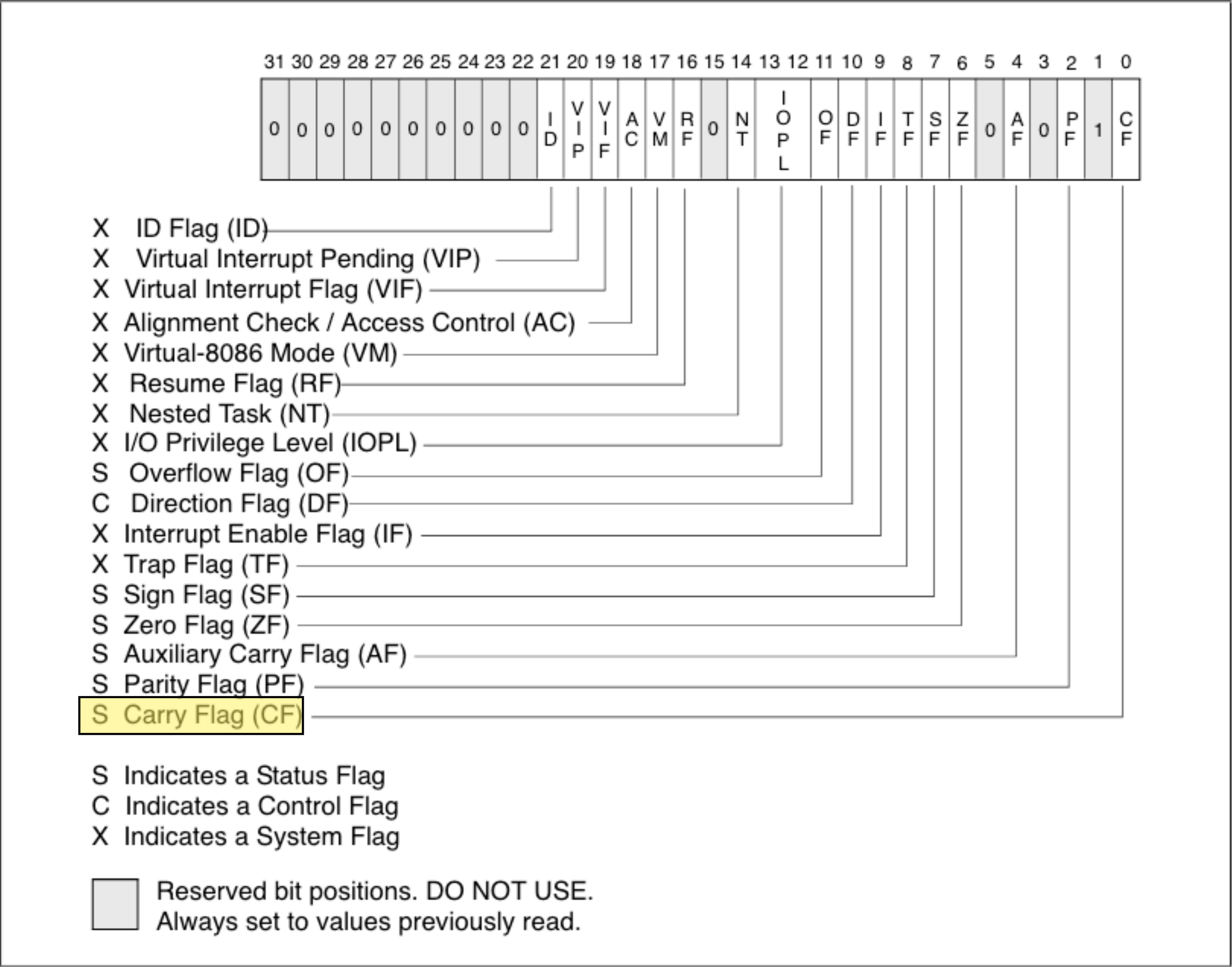


Figure 3-8. EFLAGS Register

EFLAGS (2)

- Zero flag: Set if result is zero.

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

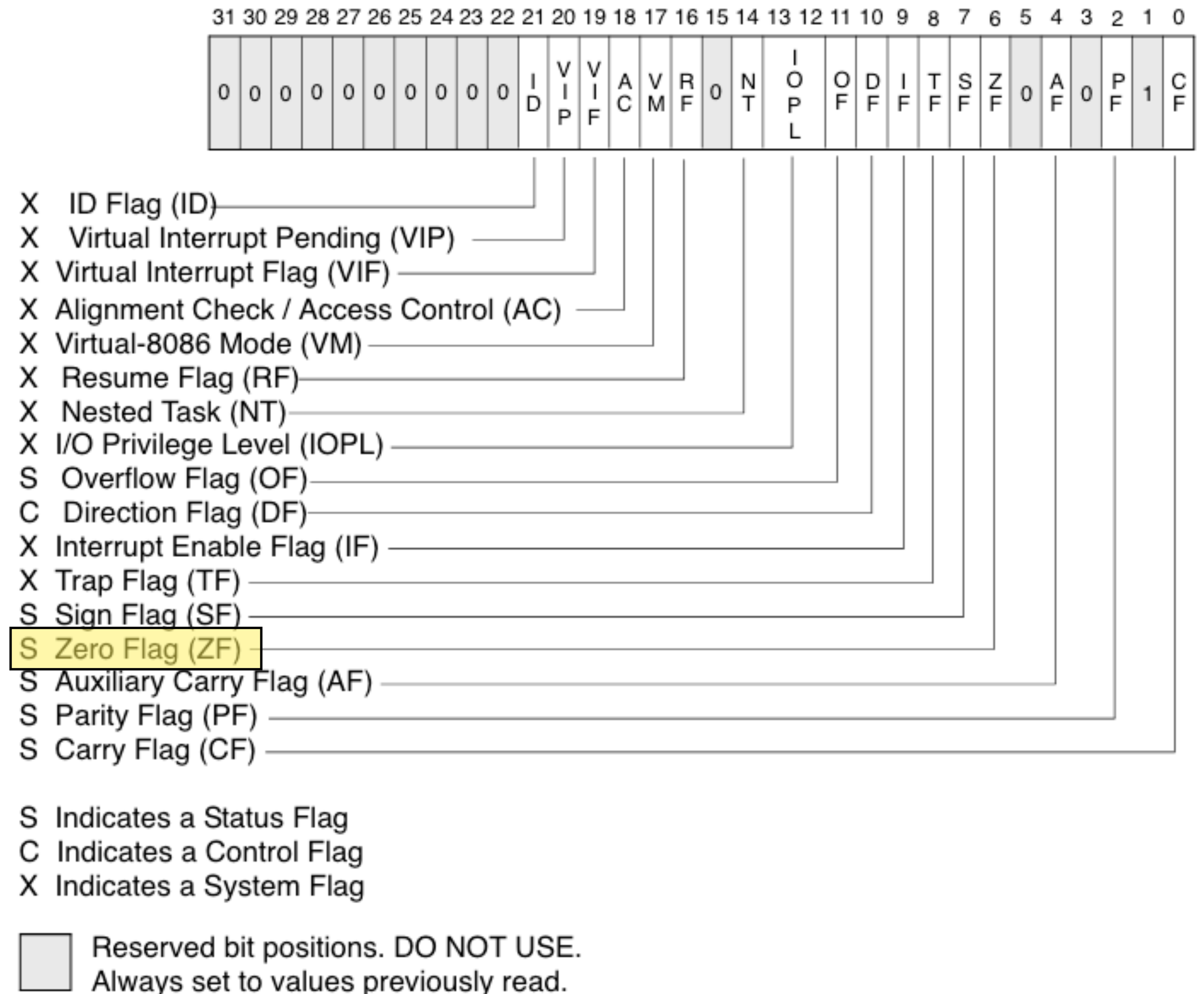


Figure 3-8. EFLAGS Register

EFLAGS (3)

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

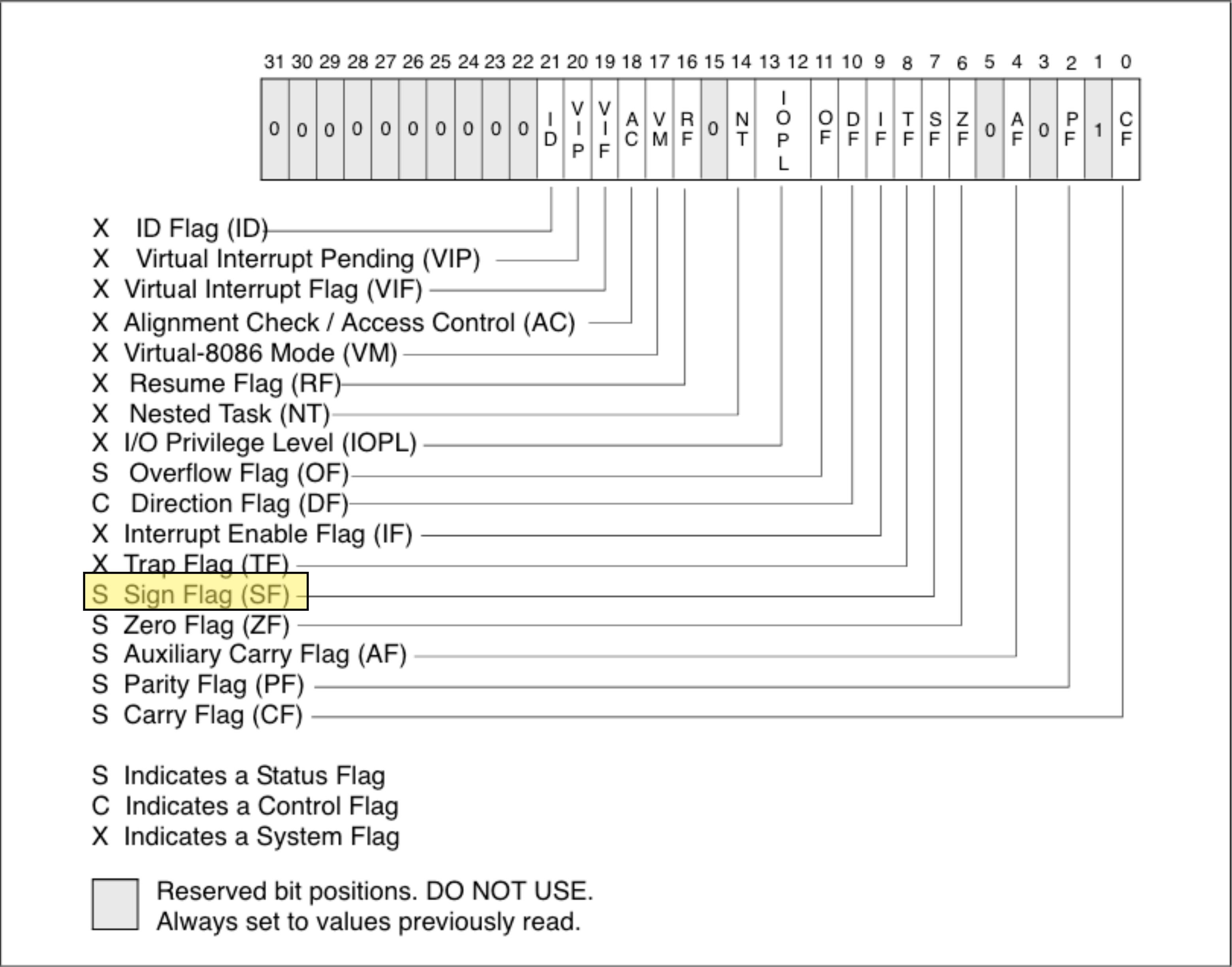


Figure 3-8. EFLAGS Register

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




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



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
```

Registers

- General purpose registers.
 - `%eax`, `%ebx`, `%ecx`, `%edx`
 - `%edi`: destination index, `%esi`: source index
- Flags register. `%eflags`
- **Instruction pointer. `%eip`**
- Stack registers. `%ebp`: base pointer, `%esp`: stack pointer
- Special registers.
 - Control registers `%cr0`, `%cr2`, `%cr3`, `%cr4`;
 - Segment registers `%cs`, `%ds`, `%es`, `%fs`, `%gs`, `%ss`
 - Global and local descriptor table registers `%gdtr`, `%ldtr`
- Other registers not used in xv6: 8 80-bit floating point registers, debug registers

Instruction pointer

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){
```

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction
```


Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction  
}
```

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction  
}
```

- %eip is simply incremented in most cases

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction  
}
```

- %eip is simply incremented in most cases
- Except special instructions

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction  
}
```

- %eip is simply incremented in most cases
- Except special instructions
 - JMP 0x1234: changes %eip to 0x1234 e.g., while loop

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction  
}
```

- %eip is simply incremented in most cases
- Except special instructions
 - JMP 0x1234: changes %eip to 0x1234 e.g., while loop
 - JP, JN, J[N]Z: jump if last result was positive, negative, zero, non-zero etc. This uses bits from EFLAGS register. e.g, if(x > 0) { .. }

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction  
}
```

- %eip is simply incremented in most cases
- Except special instructions
 - JMP 0x1234: changes %eip to 0x1234 e.g., while loop
 - JP, JN, J[N]Z: jump if last result was positive, negative, zero, non-zero etc. This uses bits from EFLAGS register. e.g, if(x > 0) { .. }
 - CALL 0x1234: Similar to JMP, additionally saves the current instruction pointer on stack e.g., function call

Instruction pointer

- Next instruction is pointed to by instruction pointer %eip

```
for(;;){  
    run next instruction  
}
```

- %eip is simply incremented in most cases
- Except special instructions
 - JMP 0x1234: changes %eip to 0x1234 e.g., while loop
 - JP, JN, J[N]Z: jump if last result was positive, negative, zero, non-zero etc. This uses bits from EFLAGS register. e.g, if(x > 0) { .. }
 - 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

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

exponent:

```
    movl 4(%esp), %ecx  
    movl 8(%esp), %eax  
    movl %ecx, %edx  
    testl %eax, %eax
```

jle .L1

.L3:

```
    imull %ecx, %edx  
    subl $1, %eax  
    jne .L3
```

.L1:

```
    movl %edx, %eax  
    ret
```

ecx = x

eax = y

edx = ecx (z = x)

bitwise and eax with eax.

SF if eax<0. ZF if eax=0.

Jump if SF or ZF (y <= 0)

z = z*x

eax-- (y--). ZF if eax=0 (y=0)

Jump back to loop if !ZF

eax = edx (return z)

Registers

- General purpose registers.
 - `%eax`, `%ebx`, `%ecx`, `%edx`
 - `%edi`: destination index, `%esi`: source index
- Flags register. `%eflags`
- Instruction pointer. `%eip`
- **Stack registers. `%ebp`: base pointer, `%esp`: stack pointer**
- Special registers.
 - Control registers `%cr0`, `%cr2`, `%cr3`, `%cr4`;
 - Segment registers `%cs`, `%ds`, `%es`, `%fs`, `%gs`, `%ss`
 - Global and local descriptor table registers `%gdtr`, `%ldtr`
- Other registers not used in xv6: 8 80-bit floating point registers, debug registers

Stack pointers

- Stack grows downwards
- `%ebp` points to return address
- `%esp` points to top of stack

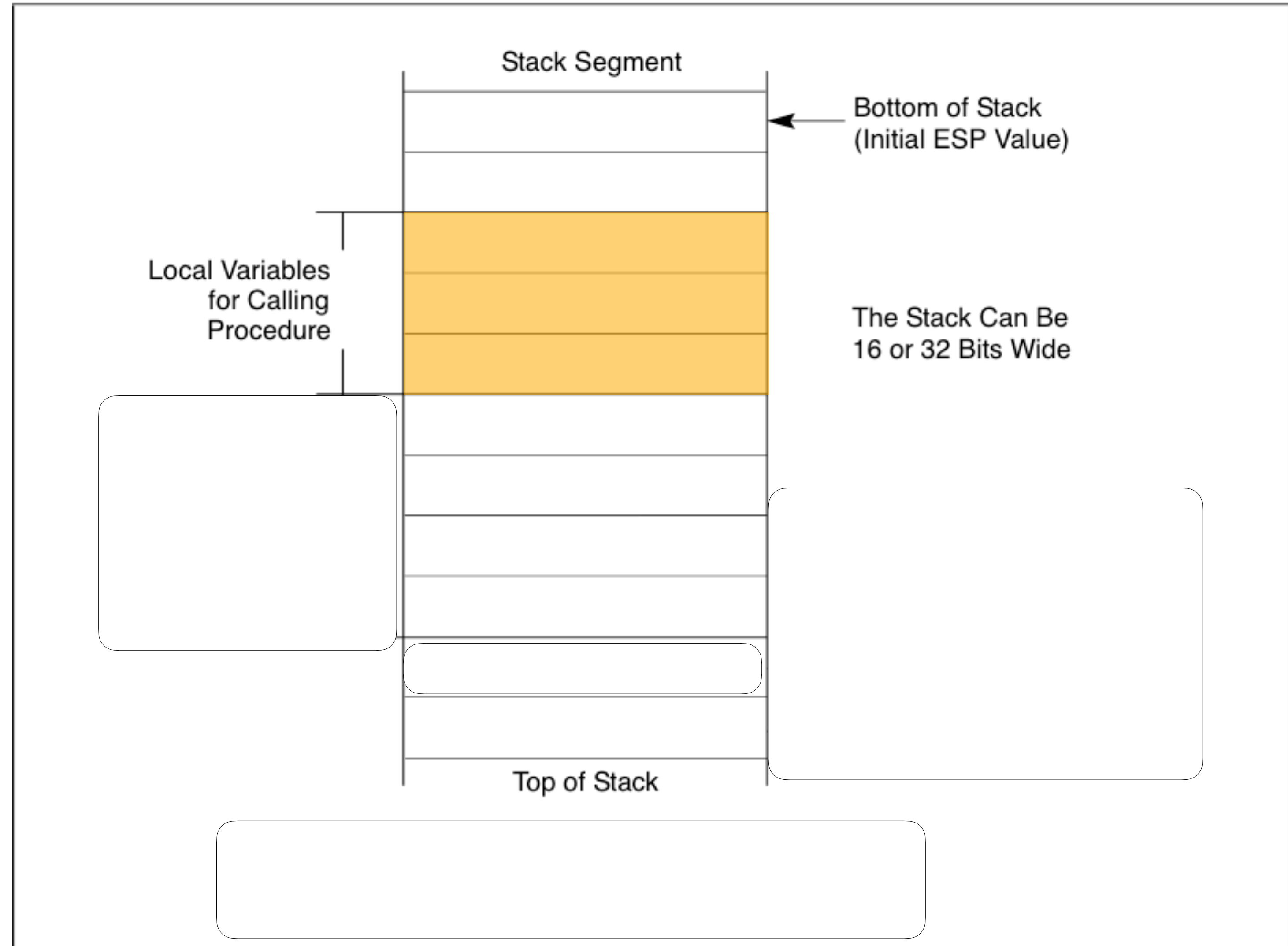


Figure 6-1. Stack Structure

Stack pointers

- Stack grows downwards
- `%ebp` points to return address
- `%esp` points to top of stack

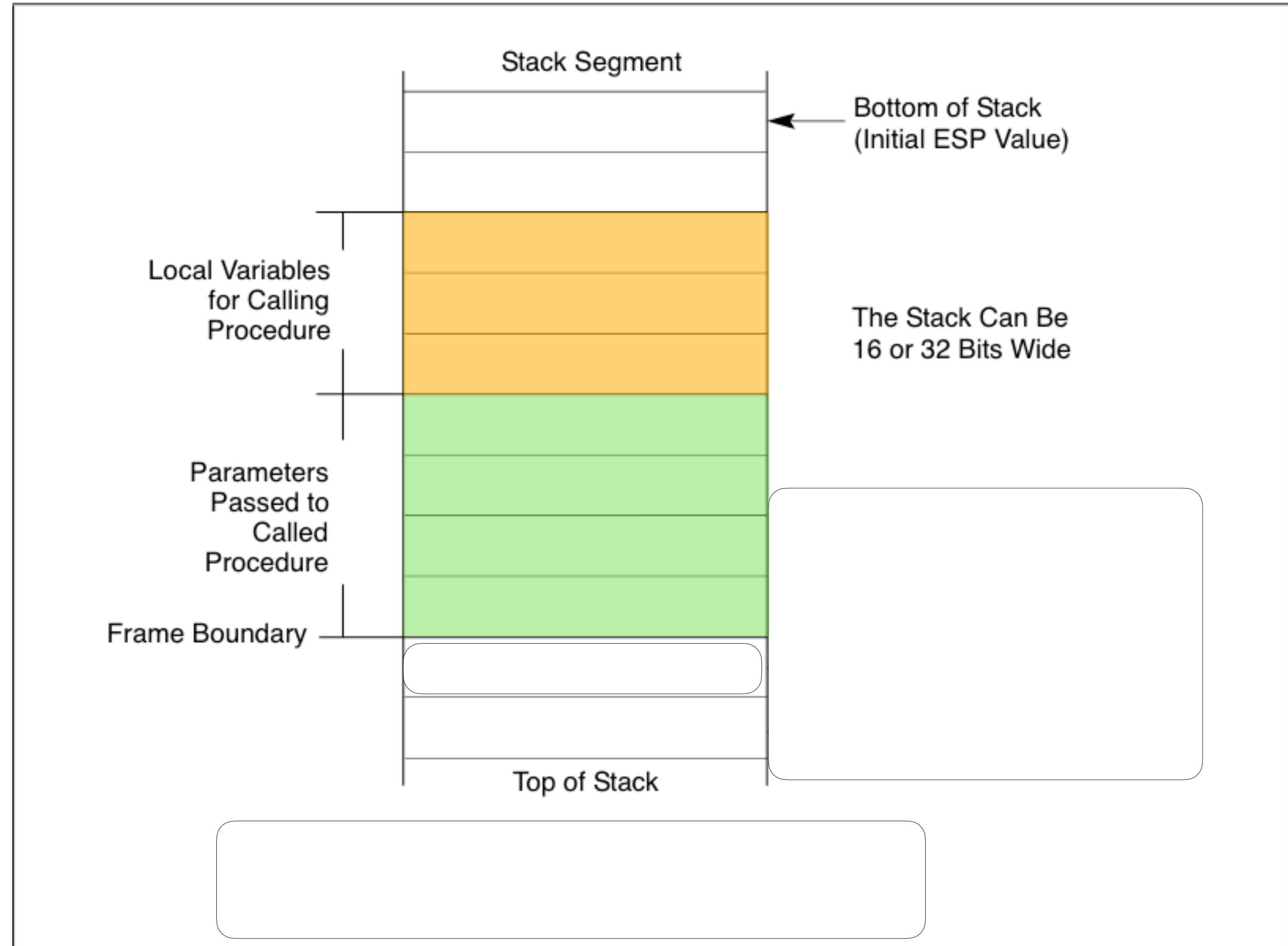


Figure 6-1. Stack Structure

Stack pointers

- Stack grows downwards
- `%ebp` points to return address
- `%esp` points to top of stack

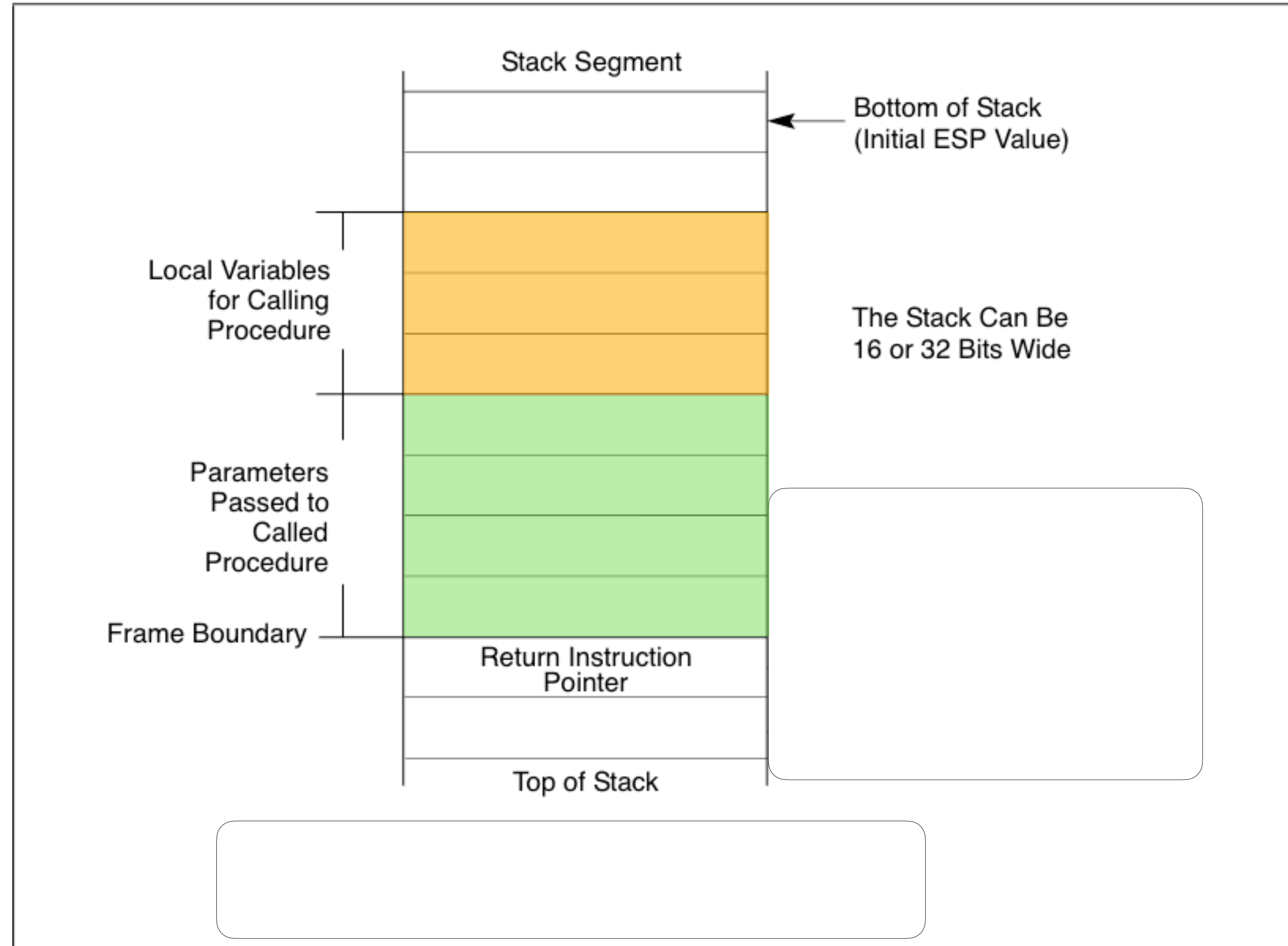


Figure 6-1. Stack Structure

Stack pointers

- Stack grows downwards
- `%ebp` points to return address
- `%esp` points to top of stack

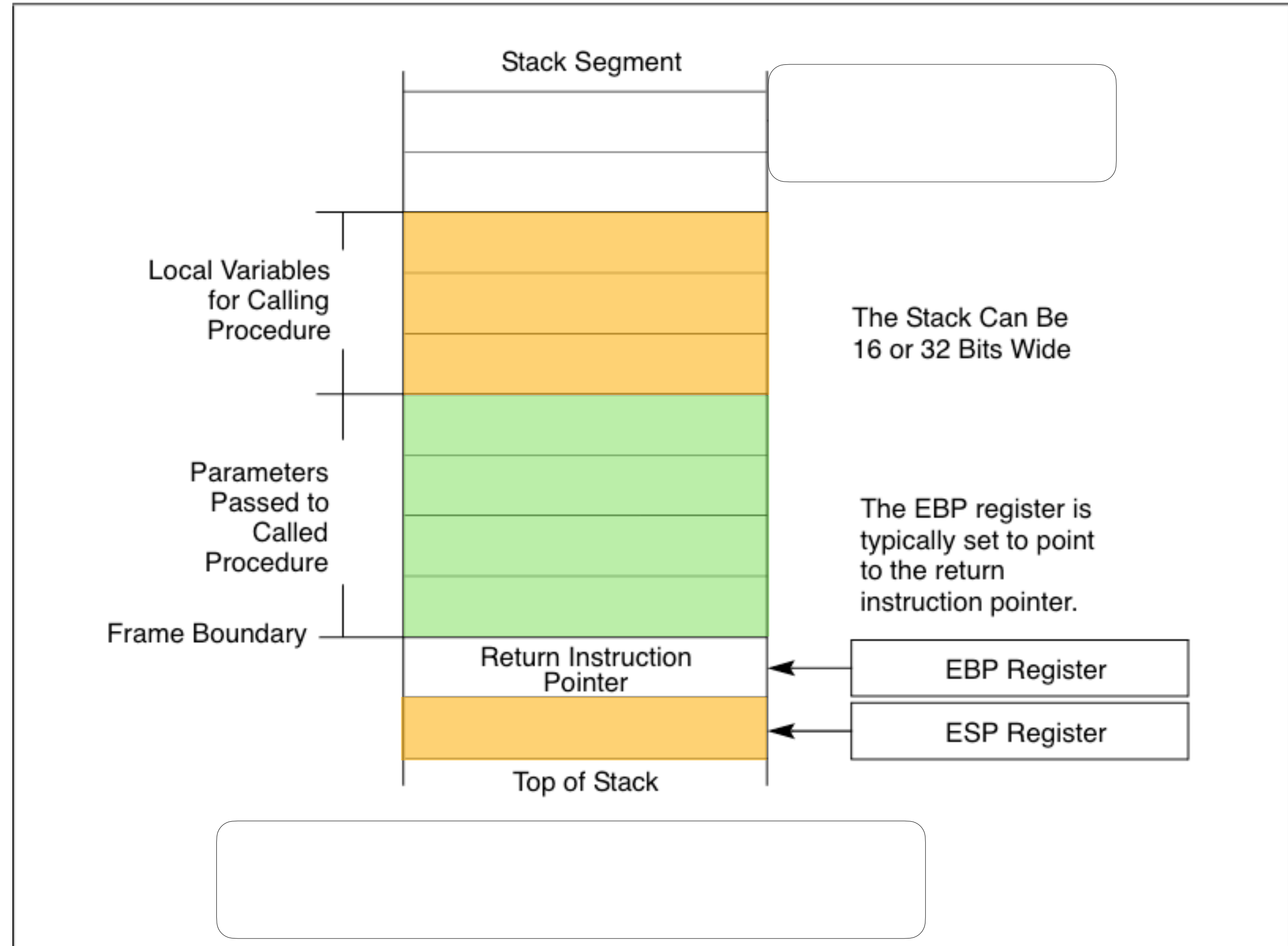


Figure 6-1. Stack Structure

Stack pointers

- Stack grows downwards
- %ebp points to return address
- %esp points to top of stack

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

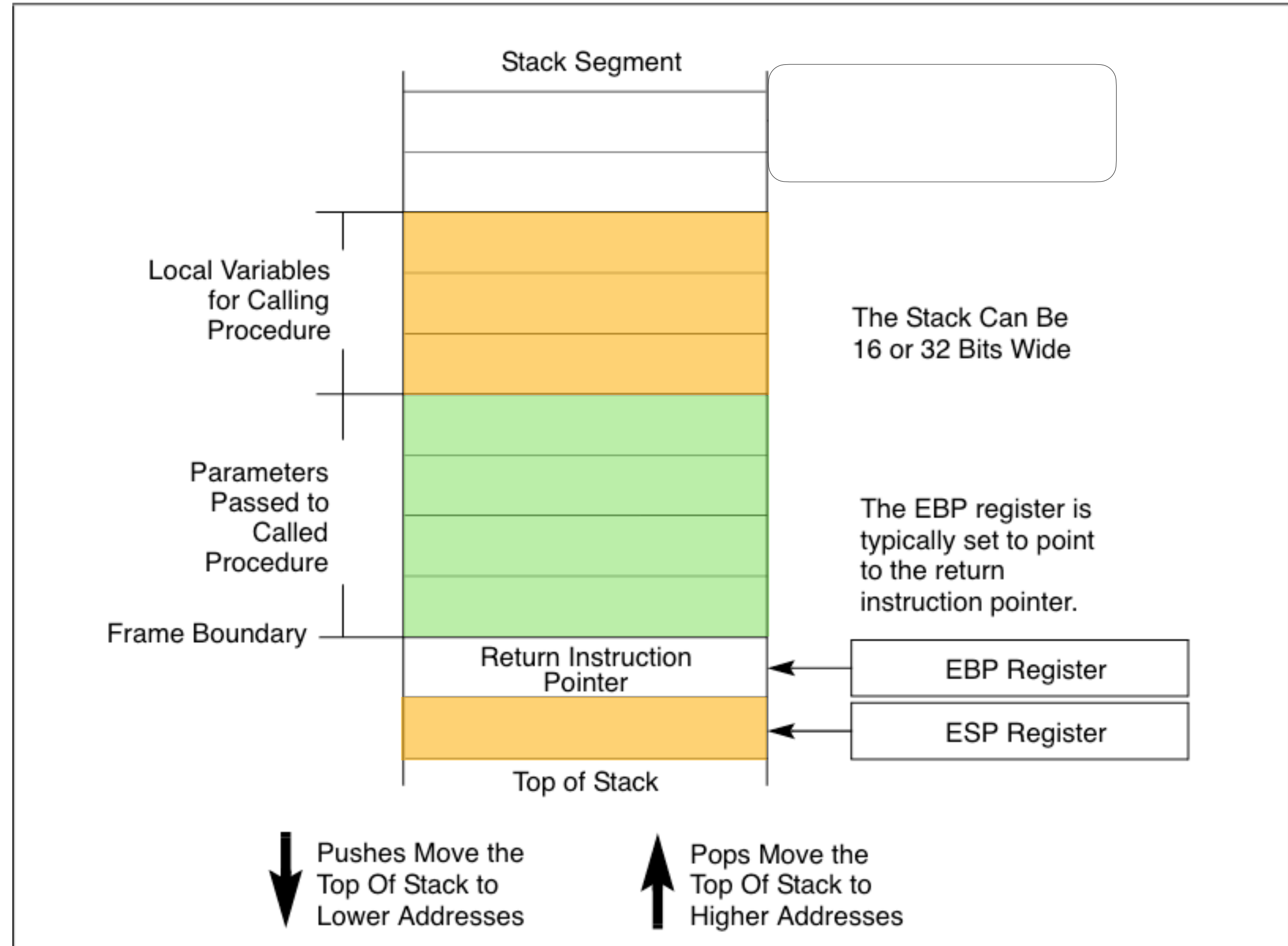


Figure 6-1. Stack Structure

Calling a function

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

Calling a function

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

- main pushes foo's parameters (x, y) on the stack

Calling a function

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

- main pushes foo's parameters (x, y) on the stack
- Executes CALL instruction to save return address on the stack and jump %eip to first instruction of foo

Calling a function

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

- main pushes foo's parameters (x, y) on the stack
- Executes CALL instruction to save return address on the stack and jump %eip to first instruction of foo
- foo reads parameters from the stack into registers, does computation on them

Calling a function

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

- main pushes foo's parameters (x, y) on the stack
- Executes CALL instruction to save return address on the stack and jump %eip to first instruction of foo
- foo reads parameters from the stack into registers, does computation on them
- foo pushes bar's parameters (z) on the stack, executes CALL instruction

Calling a function

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

- main pushes foo's parameters (x, y) on the stack
- Executes CALL instruction to save return address on the stack and jump %eip to first instruction of foo
- 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

Calling a function

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

- main pushes foo's parameters (x, y) on the stack
- Executes CALL instruction to save return address on the stack and jump %eip to first instruction of foo
- 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

Calling a function

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

- main pushes foo's parameters (x, y) on the stack
- Executes CALL instruction to save return address on the stack and jump %eip to first instruction of foo
- 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

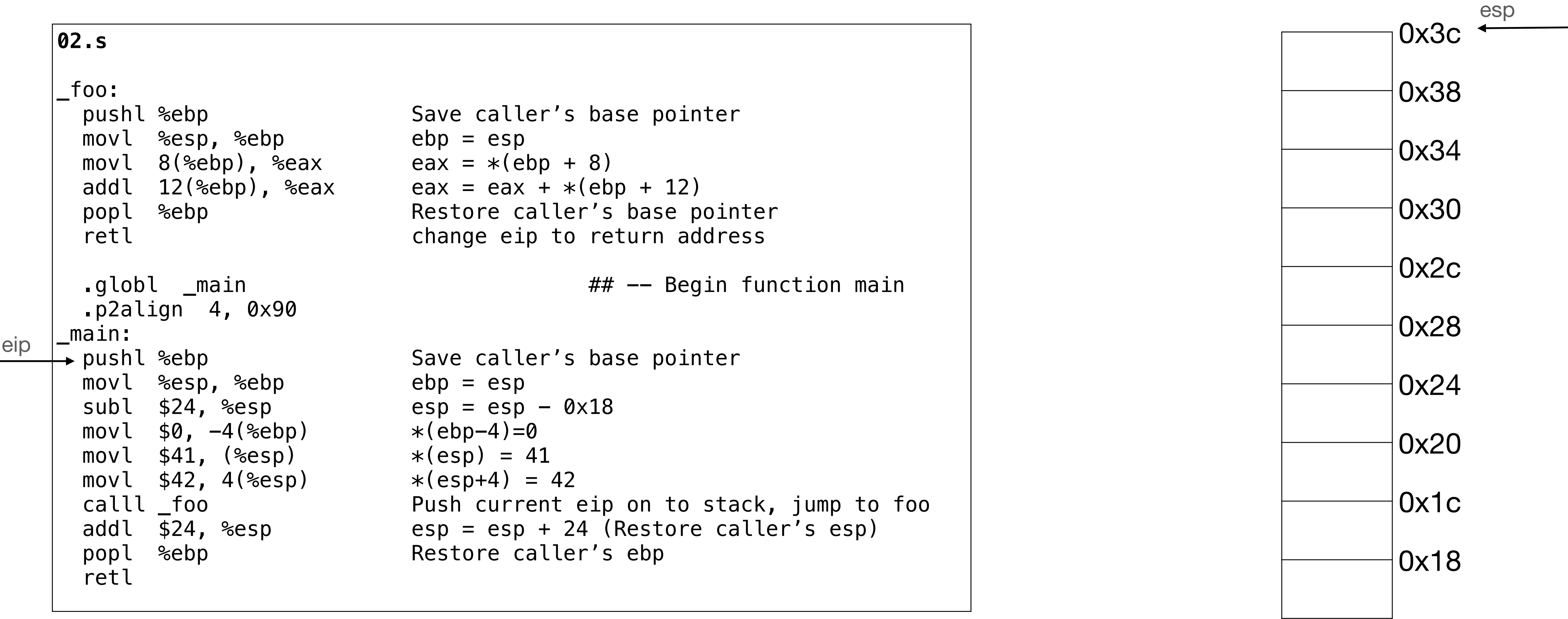
pushl %eax	subl \$4, %esp movl %eax, (%esp)
popl %eax	movl %eax, (%esp) addl \$4, %esp

02.s

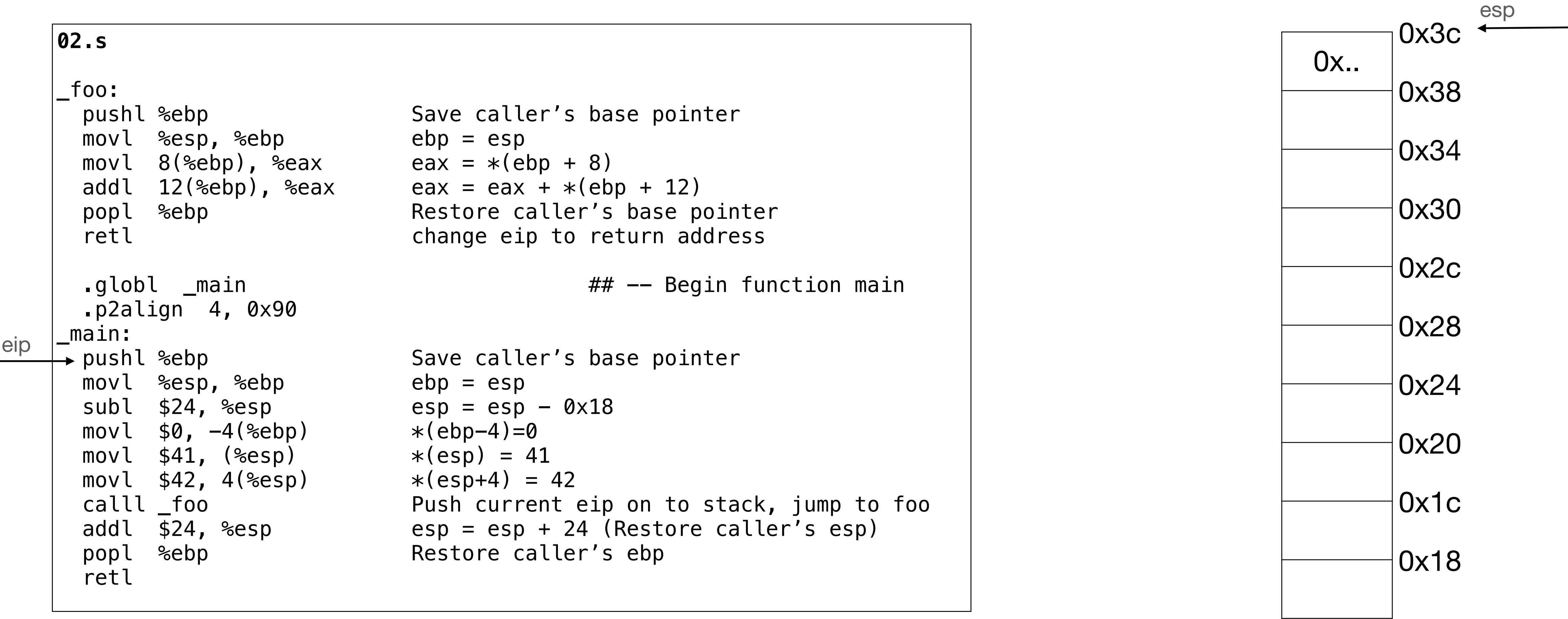
```
_foo:
    pushl %ebp                # Save caller's base pointer
    movl %esp, %ebp          # ebp = esp
    movl 8(%ebp), %eax        # eax = *(ebp + 8)
    addl 12(%ebp), %eax       # eax = eax + *(ebp + 12)
    popl %ebp                # Restore caller's base pointer
    retl                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


Function calling in action: Stack



Function calling in action: Stack



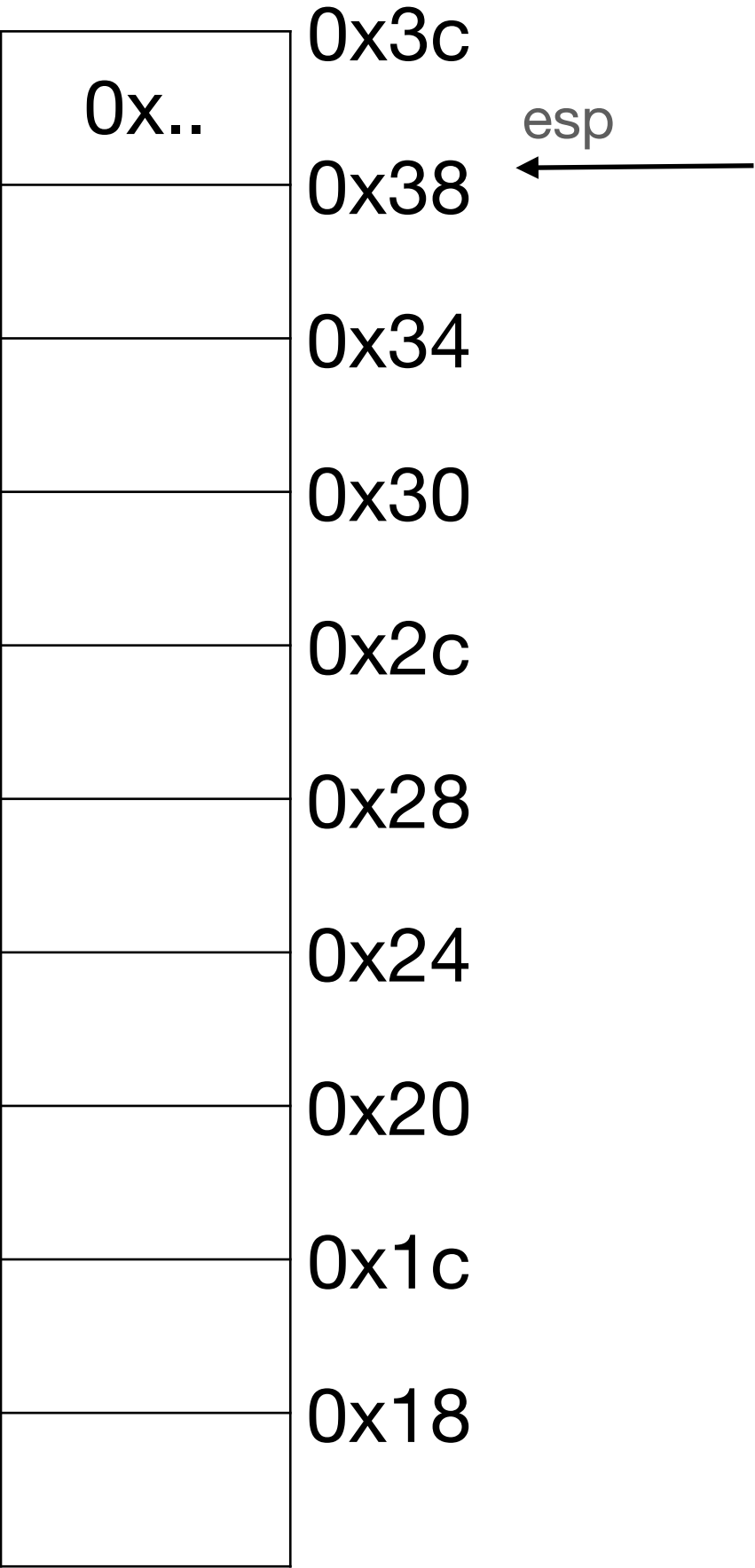
Function calling in action: Stack

ebp
→

```
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
→



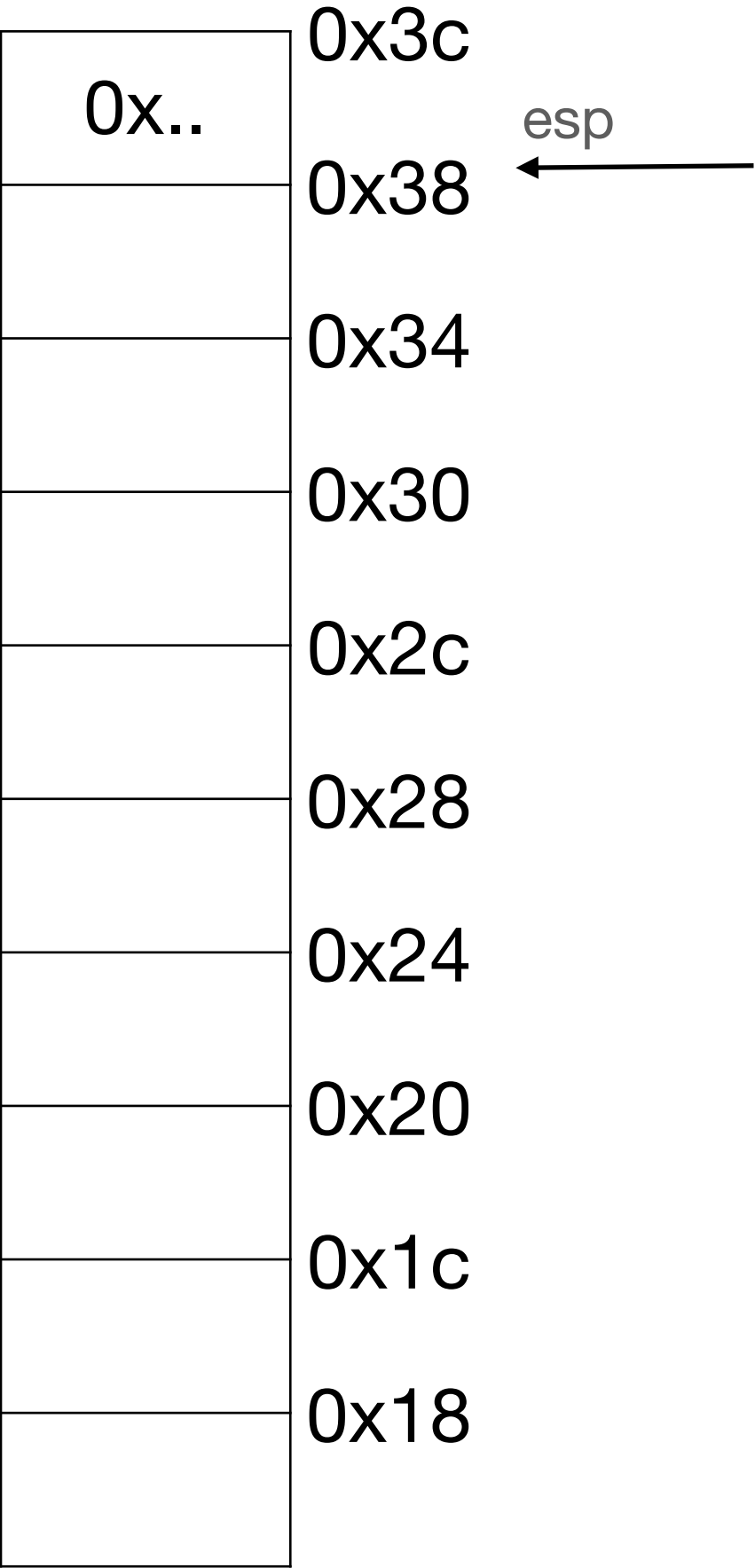
Function calling in action: Stack

ebp
→

```
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

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

Stack diagram showing memory addresses and pointers:

Address Range	Content	Pointer
0x3c - 0x38	0x..	ebp
0x38 - 0x34		
0x34 - 0x30		
0x30 - 0x2c		
0x2c - 0x28		
0x28 - 0x24		
0x24 - 0x20		
0x20 - 0x1c	0x1c	
0x1c - 0x18		esp

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

Stack diagram showing memory addresses and pointers:

Address	Content
0x3c	0x..
0x38	
0x34	
0x30	
0x2c	
0x28	
0x24	
0x20	
0x1c	
0x18	

Pointers:
ebp points to the top of the stack (0x3c).
esp points to the current stack pointer (0x18).

Function calling in action: Stack

02.s

eip

→

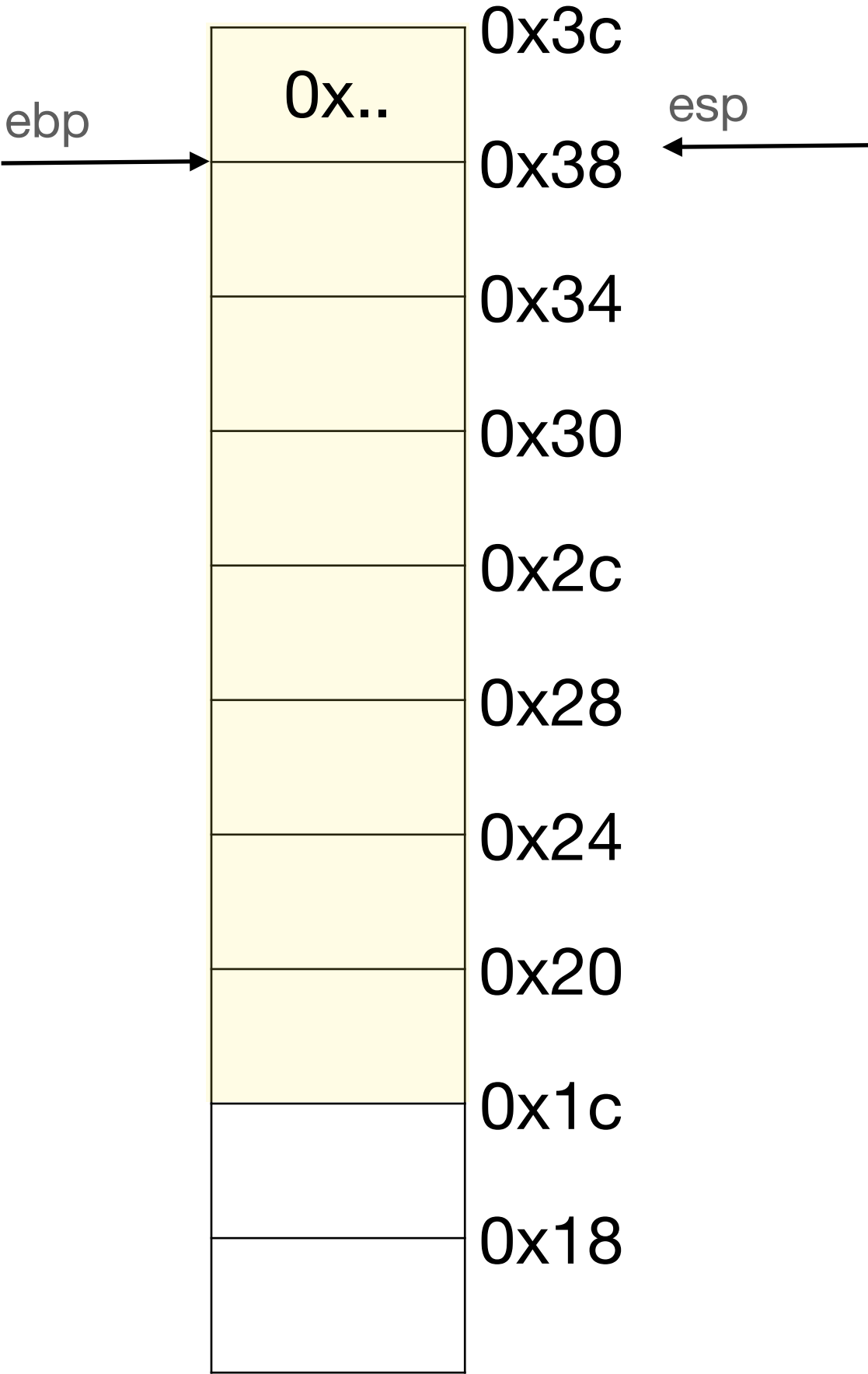
```
_foo:
    pushl %ebp
    movl  %esp, %ebp
    movl  8(%ebp), %eax
    addl  12(%ebp), %eax
    popl  %ebp
    retl

    .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
```

```
                Save caller's base pointer
                ebp = esp
                eax = *(ebp + 8)
                eax = eax + *(ebp + 12)
                Restore caller's base pointer
                change eip to return address

                ## -- Begin function main

                Save caller's base pointer
                ebp = esp
                esp = esp - 0x18
                *(ebp-4)=0
                *(esp) = 41
                *(esp+4) = 42
                Push current eip on to stack, jump to foo
                esp = esp + 24 (Restore caller's esp)
                Restore caller's ebp
```



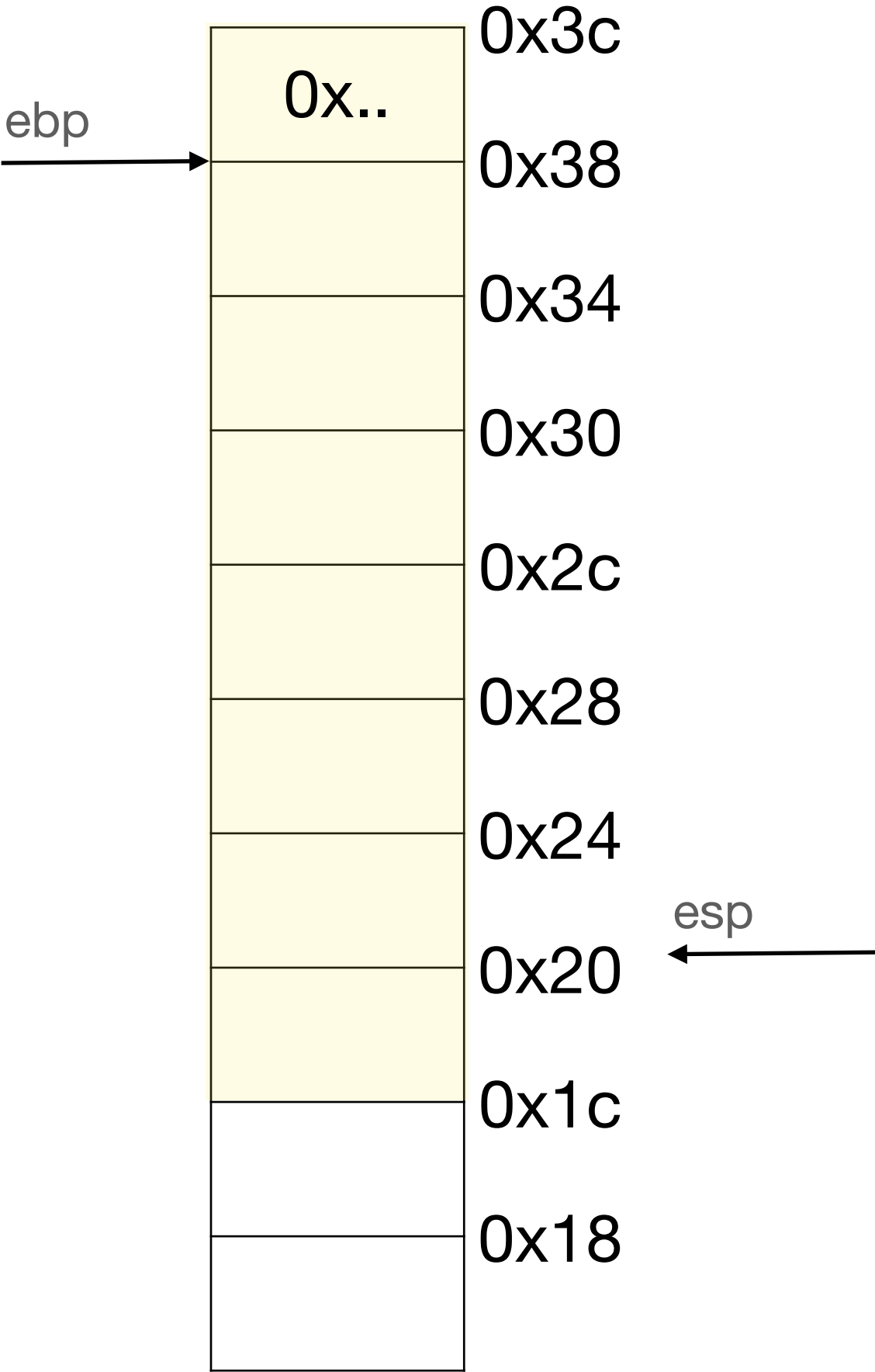
Function calling in action: Stack

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

02.s

_foo:

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

Save caller's base pointer
ebp = esp
eax = *(ebp + 8)
eax = eax + *(ebp + 12)
Restore caller's base pointer
change eip to return address

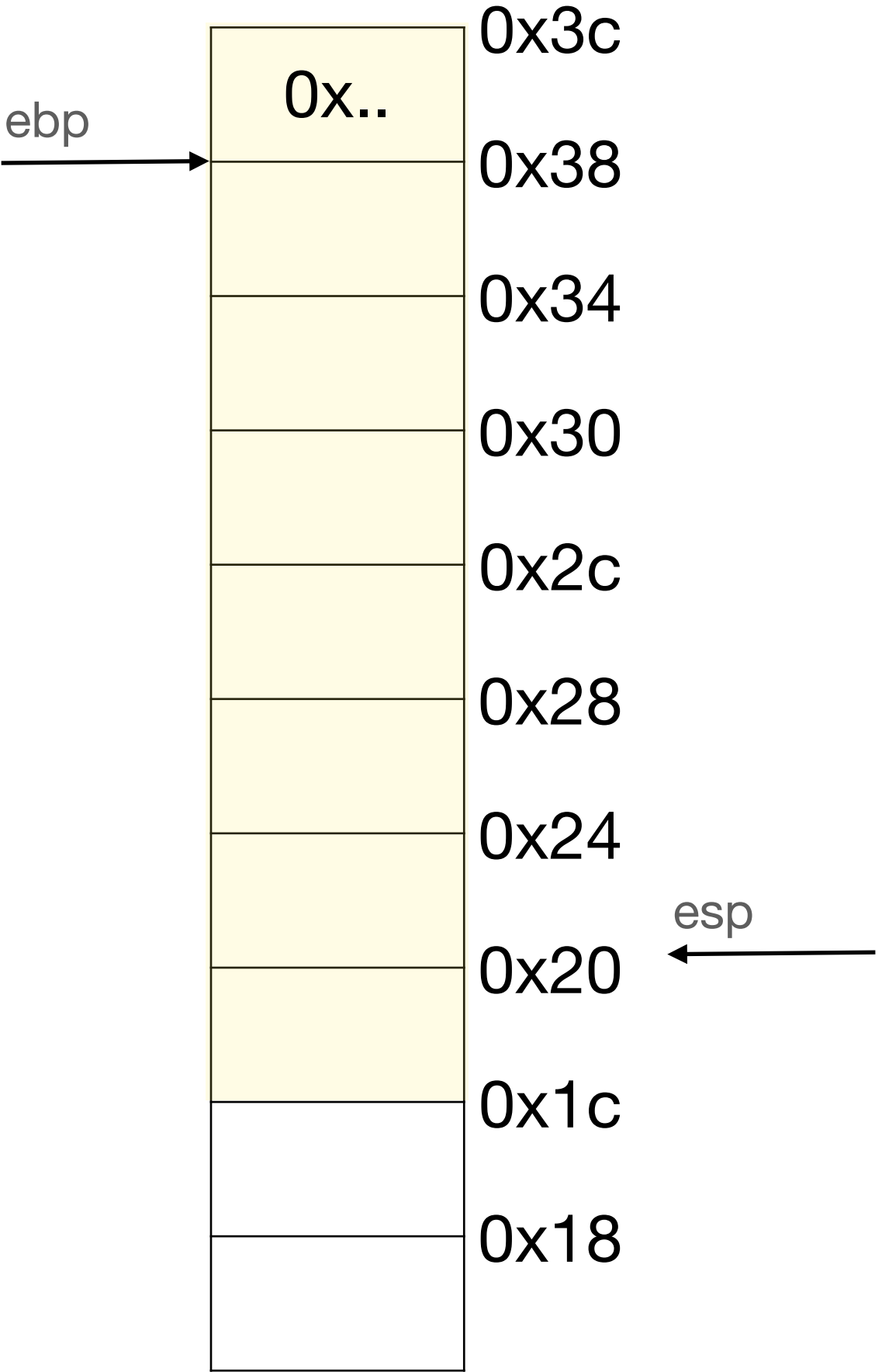
```
.globl _main
.p2align 4, 0x90
```

-- Begin function main

_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
```

Save caller's base pointer
ebp = esp
esp = esp - 0x18
*(ebp-4)=0
*(esp) = 41
*(esp+4) = 42
Push current eip on to stack, jump to foo
esp = esp + 24 (Restore caller's esp)
Restore caller's ebp



Function calling in action: Stack

02.s

```
foo:
```

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

```
Save caller's base pointer
ebp = esp
eax = *(ebp + 8)
eax = eax + *(ebp + 12)
Restore caller's base pointer
change eip to return address
```

```
.globl _main
.p2align 4, 0x90
```

```
## -- Begin function main
```

```

main:

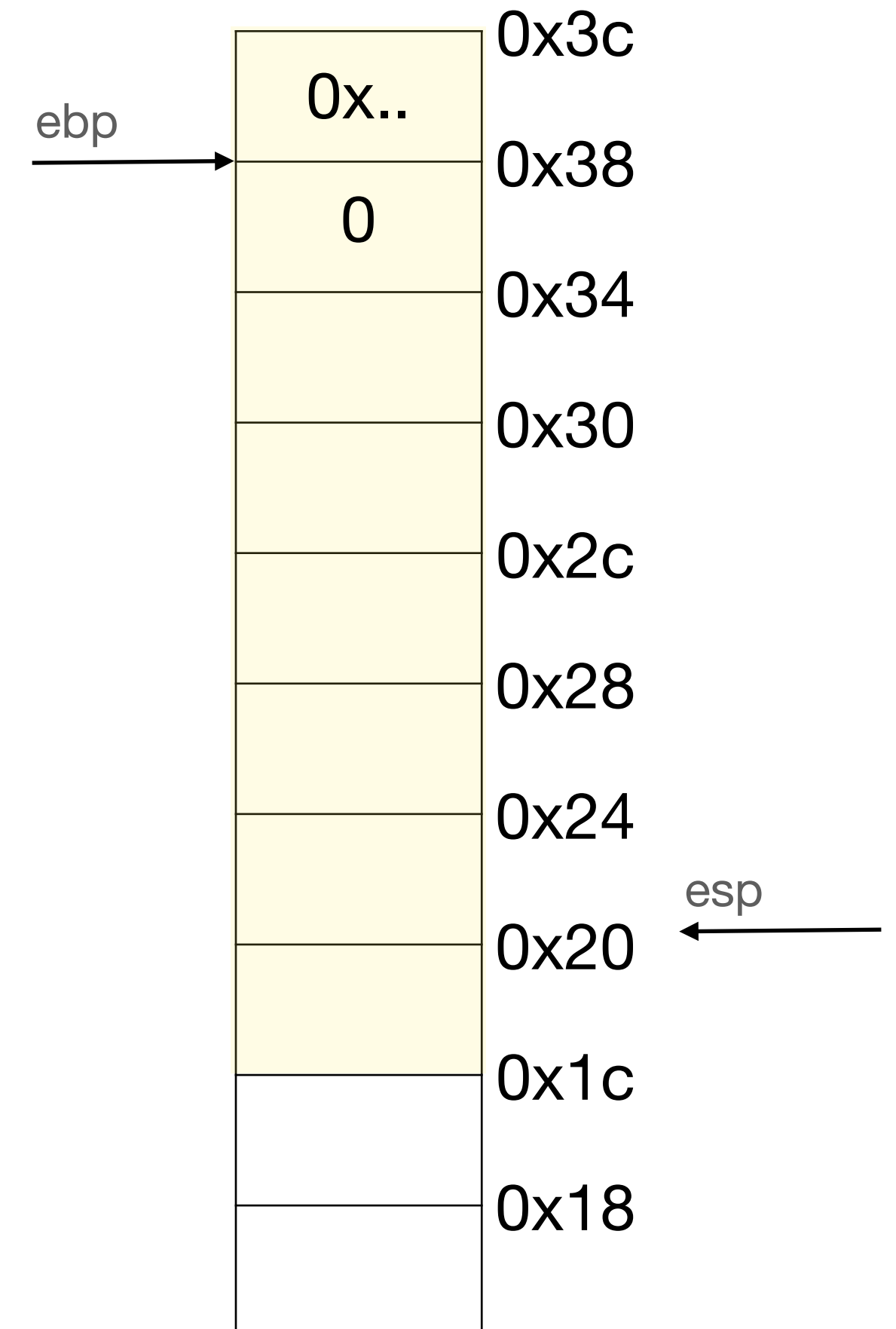
```

```

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

```

```
Save caller's base pointer
ebp = esp
esp = esp - 0x18
*(ebp-4)=0
*(esp) = 41
*(esp+4) = 42
Push current eip on to stack, jump to foo
esp = esp + 24 (Restore caller's esp)
Restore caller's ebp
```



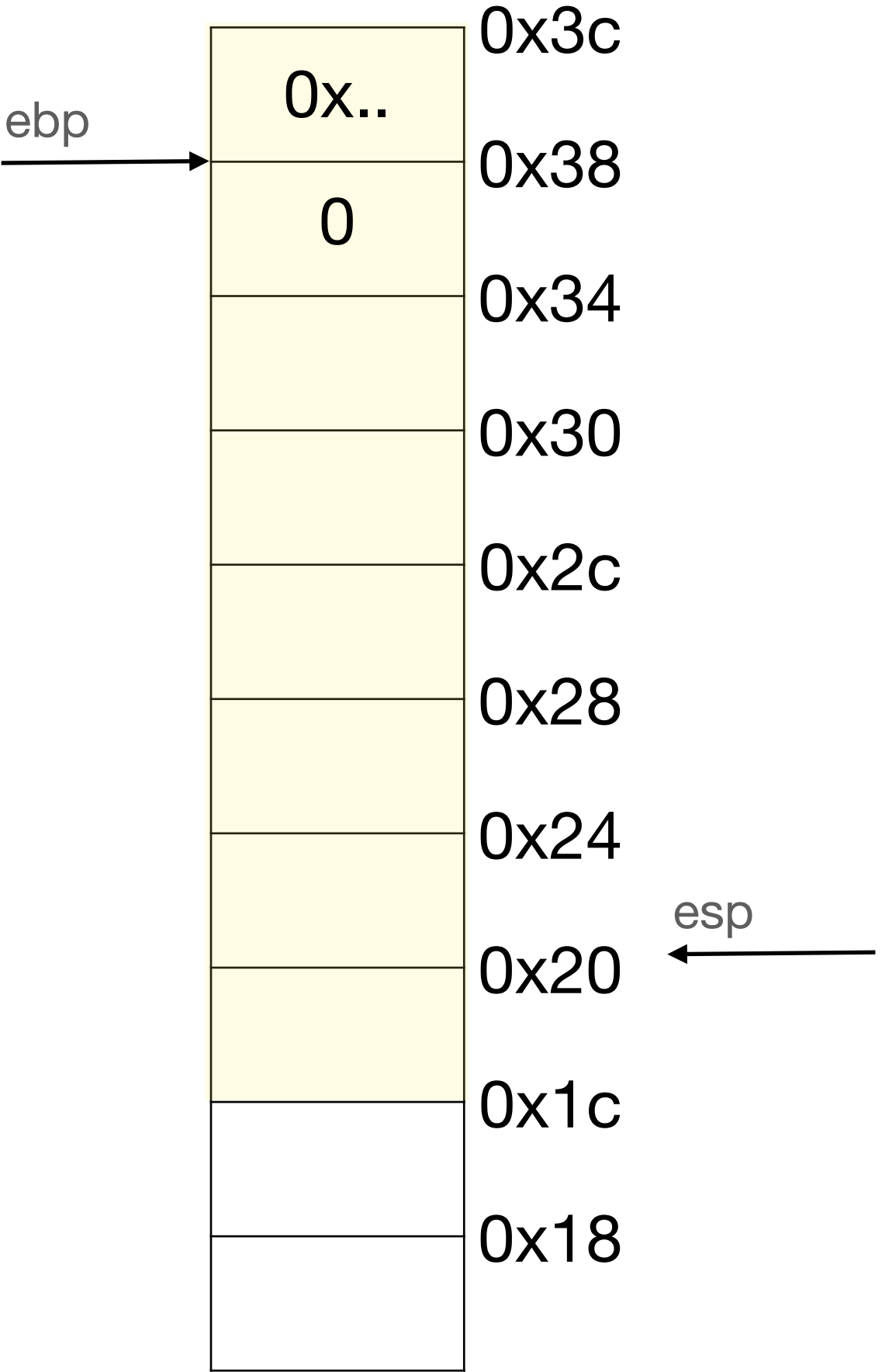
Function calling in action: Stack

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

02.s

```
foo:
```

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

```
Save caller's base pointer
ebp = esp
eax = *(ebp + 8)
eax = eax + *(ebp + 12)
Restore caller's base pointer
change eip to return address
```

```
.globl _main
.p2align 4, 0x90
```

```
## -- Begin function main
```

```

main:

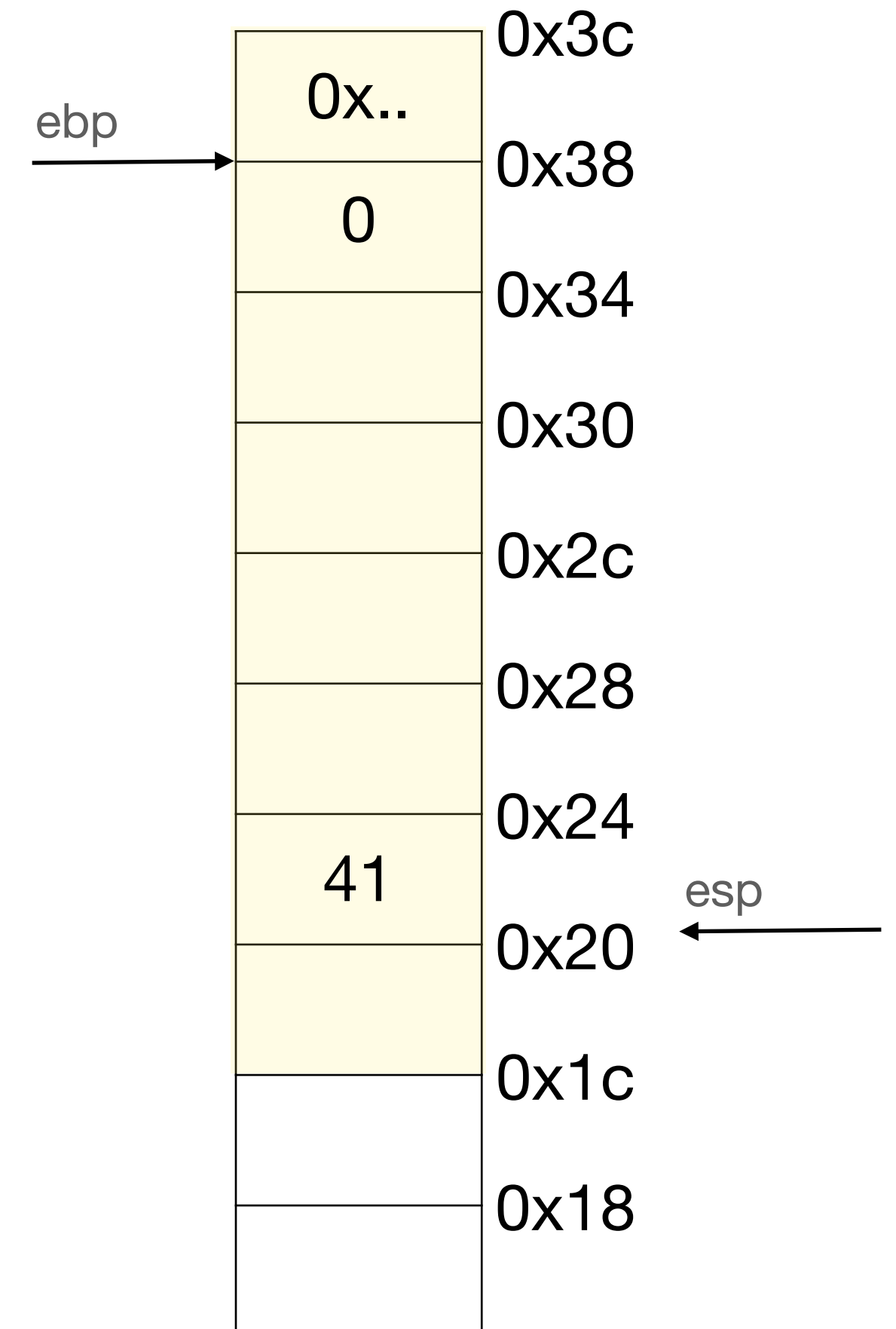
```

```

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

```

```
Save caller's base pointer
ebp = esp
esp = esp - 0x18
*(ebp-4)=0
*(esp) = 41
*(esp+4) = 42
Push current eip on to stack, jump to foo
esp = esp + 24 (Restore caller's esp)
Restore caller's ebp
```



Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

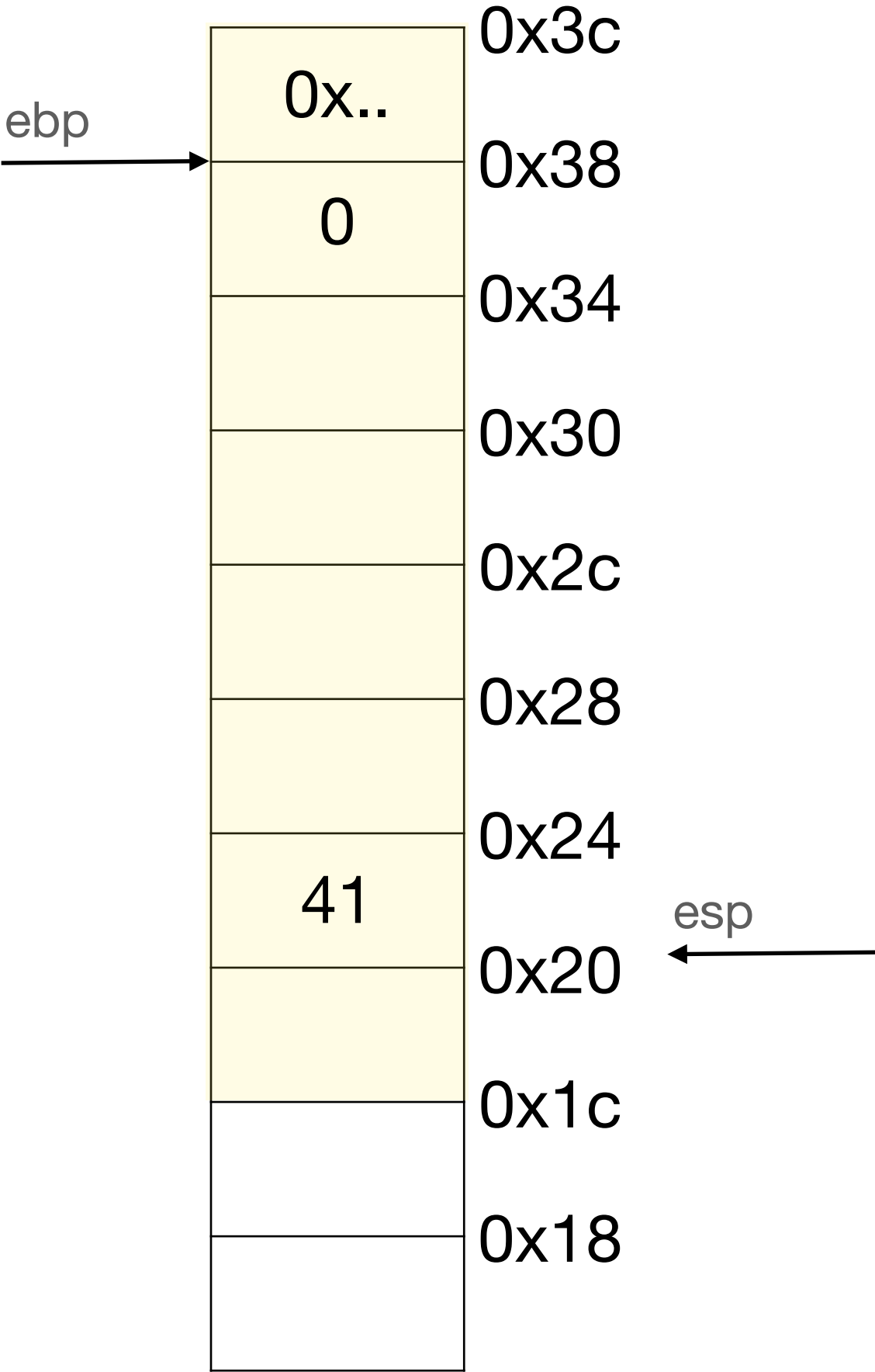
*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp



Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

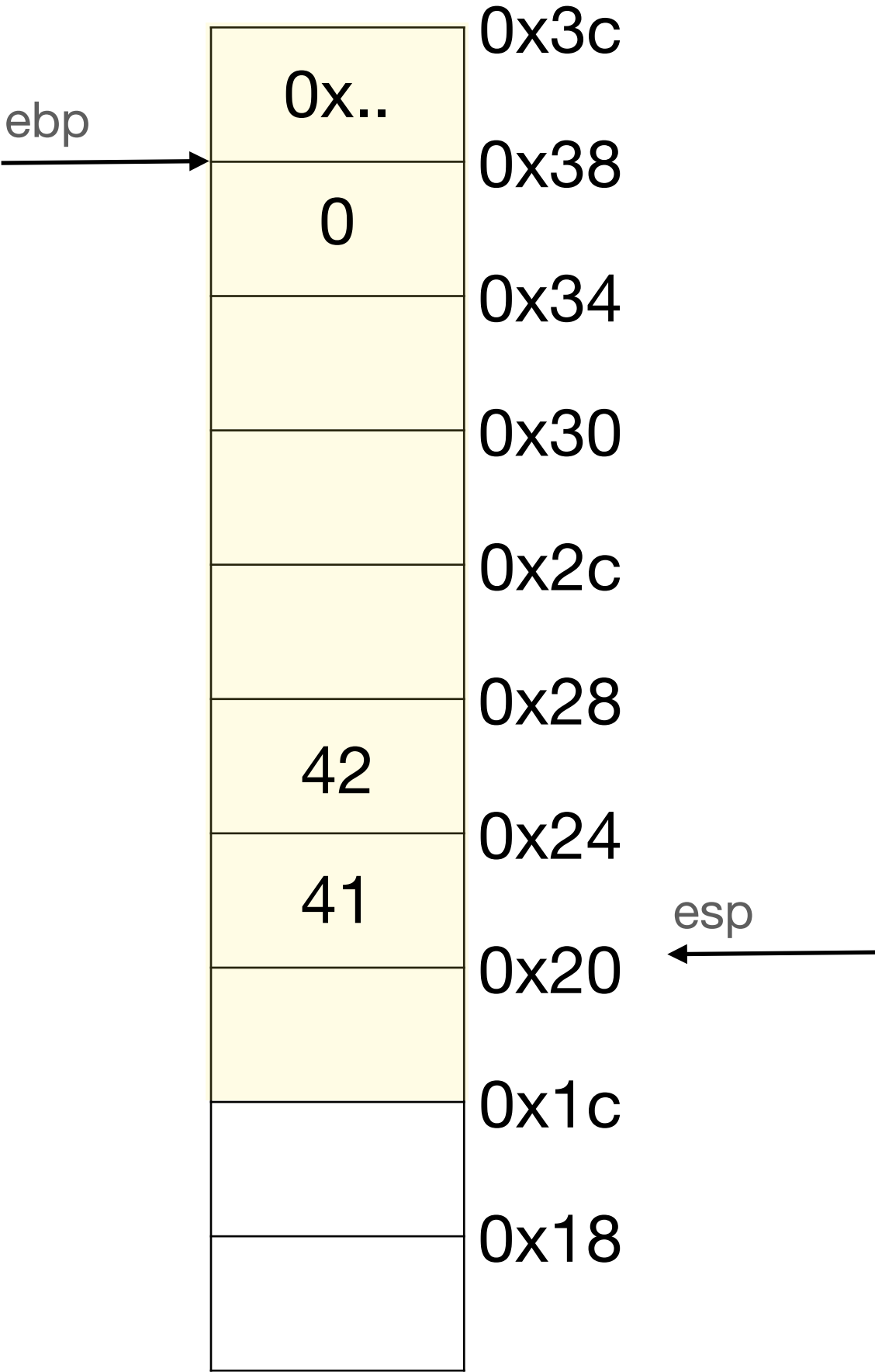
*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp



Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

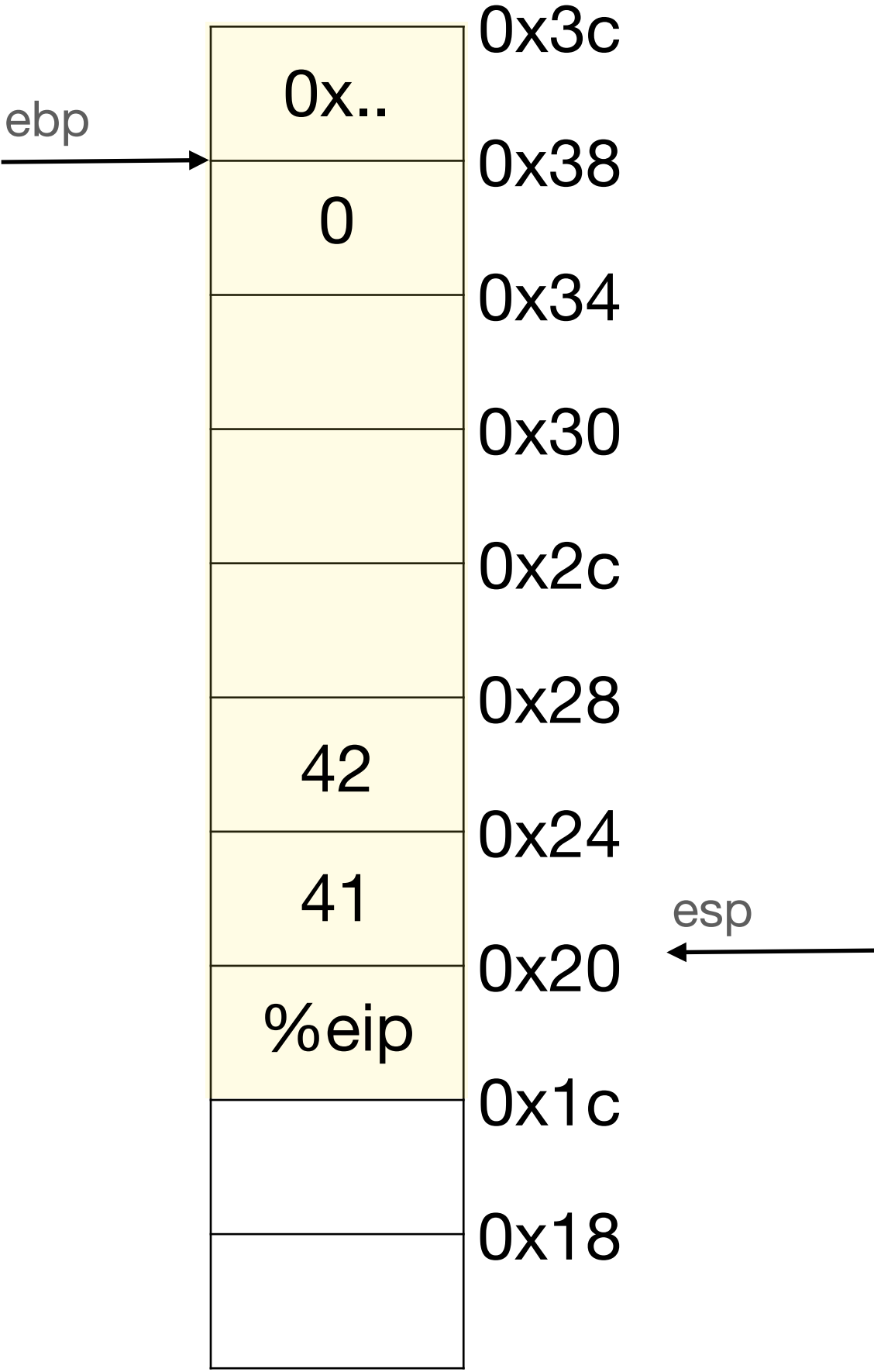
Stack diagram showing memory addresses and values:

Address	Value
0x3c	0x..
0x38	0
0x34	
0x30	
0x2c	
0x28	42
0x24	41
0x20	
0x1c	
0x18	

The **eip** register points to address 0x38 (containing 0). The **esp** register points to address 0x20.

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

02.s

eip

→

calll _foo

addl \$24, %esp

popl %ebp

retl

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

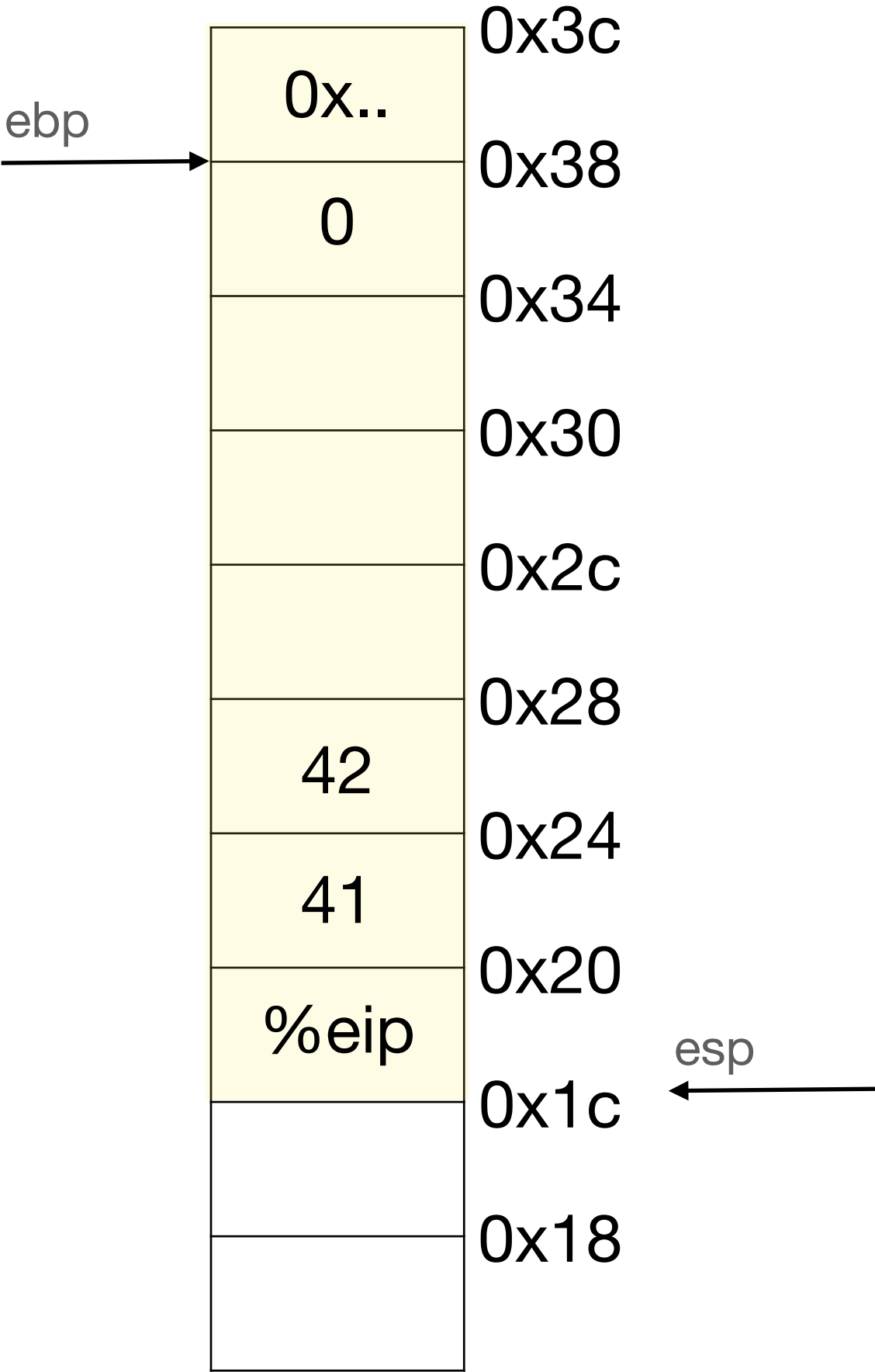
*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp



Function calling in action: Stack

02.s

eip

→

`_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`

`Save caller's base pointer
ebp = esp
eax = *(ebp + 8)
eax = eax + *(ebp + 12)
Restore caller's base pointer
change eip to return address`

`## -- Begin function main`

`Save caller's base pointer
ebp = esp
esp = esp - 0x18
*(ebp-4)=0
*(esp) = 41
*(esp+4) = 42
Push current eip on to stack, jump to foo
esp = esp + 24 (Restore caller's esp)
Restore caller's ebp`

0x3c	0x..	ebp →
0x38	0	
0x34		
0x30		
0x2c		
0x28	42	
0x24	41	
0x20	%eip	
0x1c		← esp
0x18		

Function calling in action: Stack

02.s

eip

→

`_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`

Save caller's base pointer

`ebp = esp`

`eax = *(ebp + 8)`

`eax = eax + *(ebp + 12)`

Restore caller's base pointer

change eip to return address

`## -- Begin function main`

Save caller's base pointer

`ebp = esp`

`esp = esp - 0x18`

`*(ebp-4)=0`

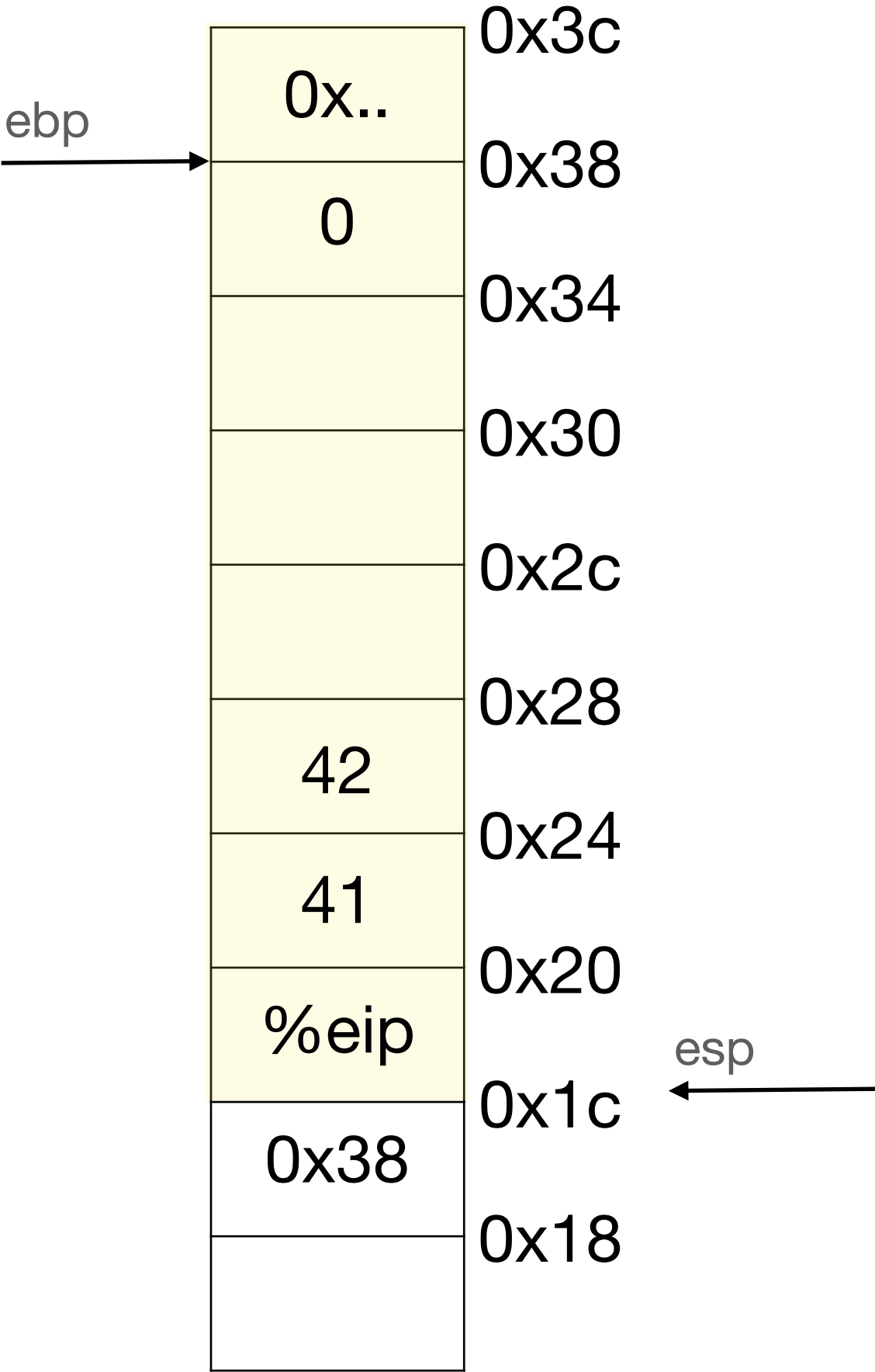
`*(esp) = 41`

`*(esp+4) = 42`

Push current eip on to stack, jump to foo

`esp = esp + 24 (Restore caller's esp)`

Restore caller's ebp



Function calling in action: Stack

02.s

eip

→

`_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`

`Save caller's base pointer
ebp = esp
eax = *(ebp + 8)
eax = eax + *(ebp + 12)
Restore caller's base pointer
change eip to return address`

`## -- Begin function main`

`Save caller's base pointer
ebp = esp
esp = esp - 0x18
*(ebp-4)=0
*(esp) = 41
*(esp+4) = 42
Push current eip on to stack, jump to foo
esp = esp + 24 (Restore caller's esp)
Restore caller's ebp`

	0x3c
0x..	
0	0x38
	0x34
	0x30
	0x2c
42	0x28
41	0x24
%eip	0x20
0x38	0x1c
	0x18 ← esp

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

	0x3c
ebp →	0x..
	0x38
	0
	0x34
	0x30
	0x2c
	0x28
	42
	0x24
	41
	0x20
	%eip
	0x1c
	0x38
	0x18

esp ←

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

0x3c	0x..
0x38	0
0x34	
0x30	
0x2c	
0x28	42
0x24	41
0x20	%eip
0x1c	0x38
0x18	

ebp → 0x38 ← esp

Function calling in action: Stack

02.s

eip

→

```
_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
```

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

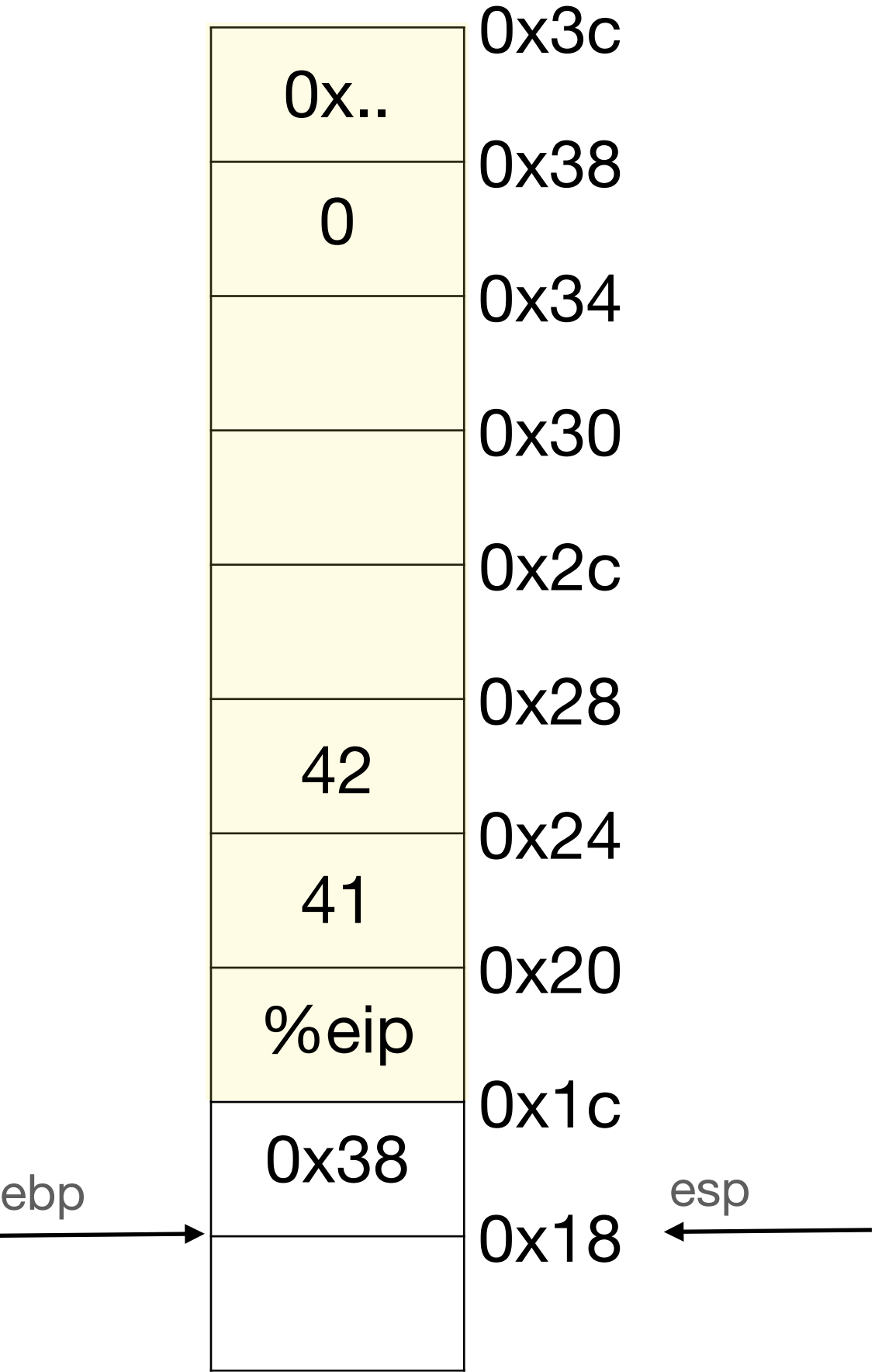
*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp



Function calling in action: Stack

02.s

eip

→

```
_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
```

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

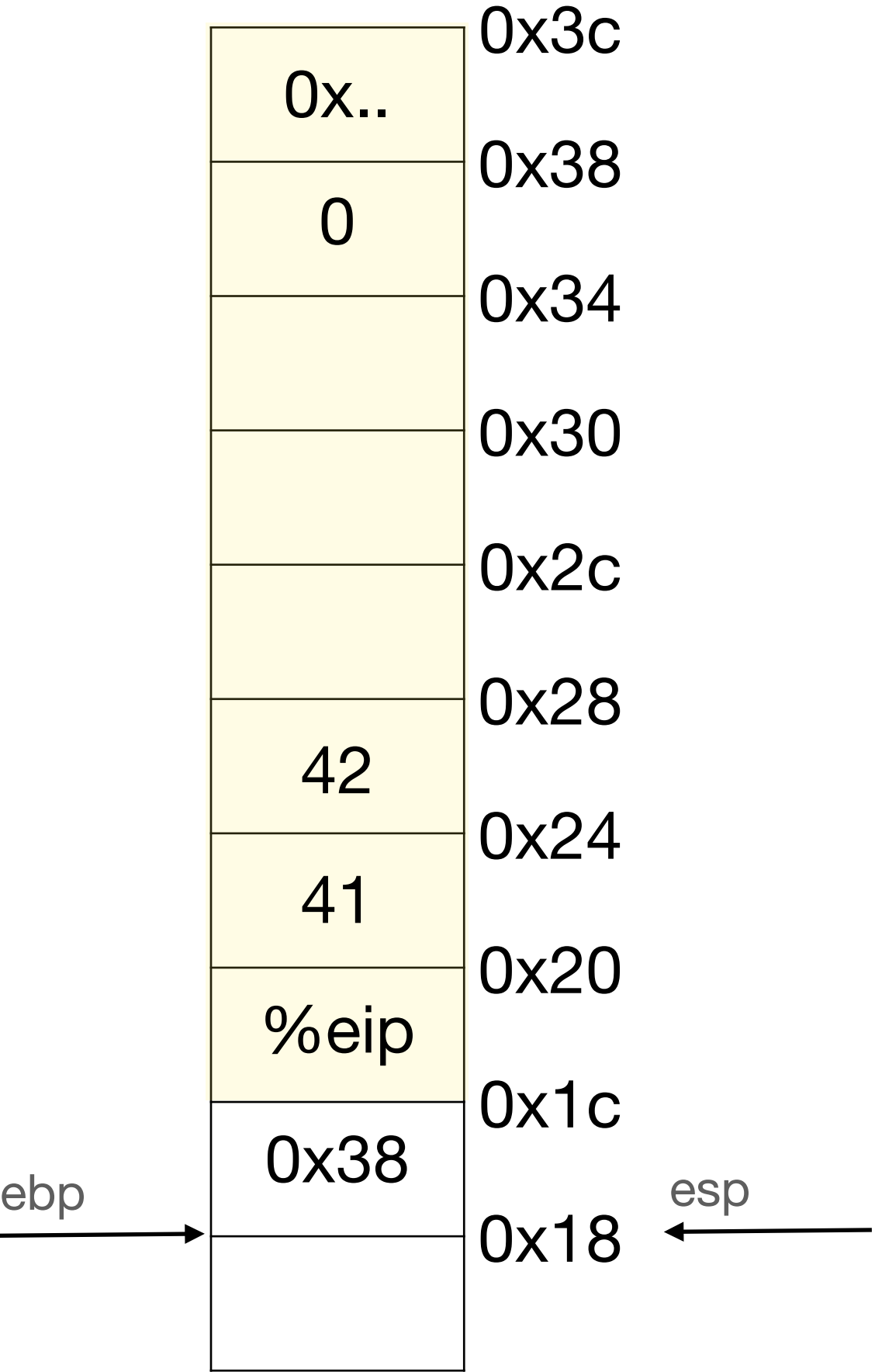
*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp



Function calling in action: Stack

02.s

eip

→

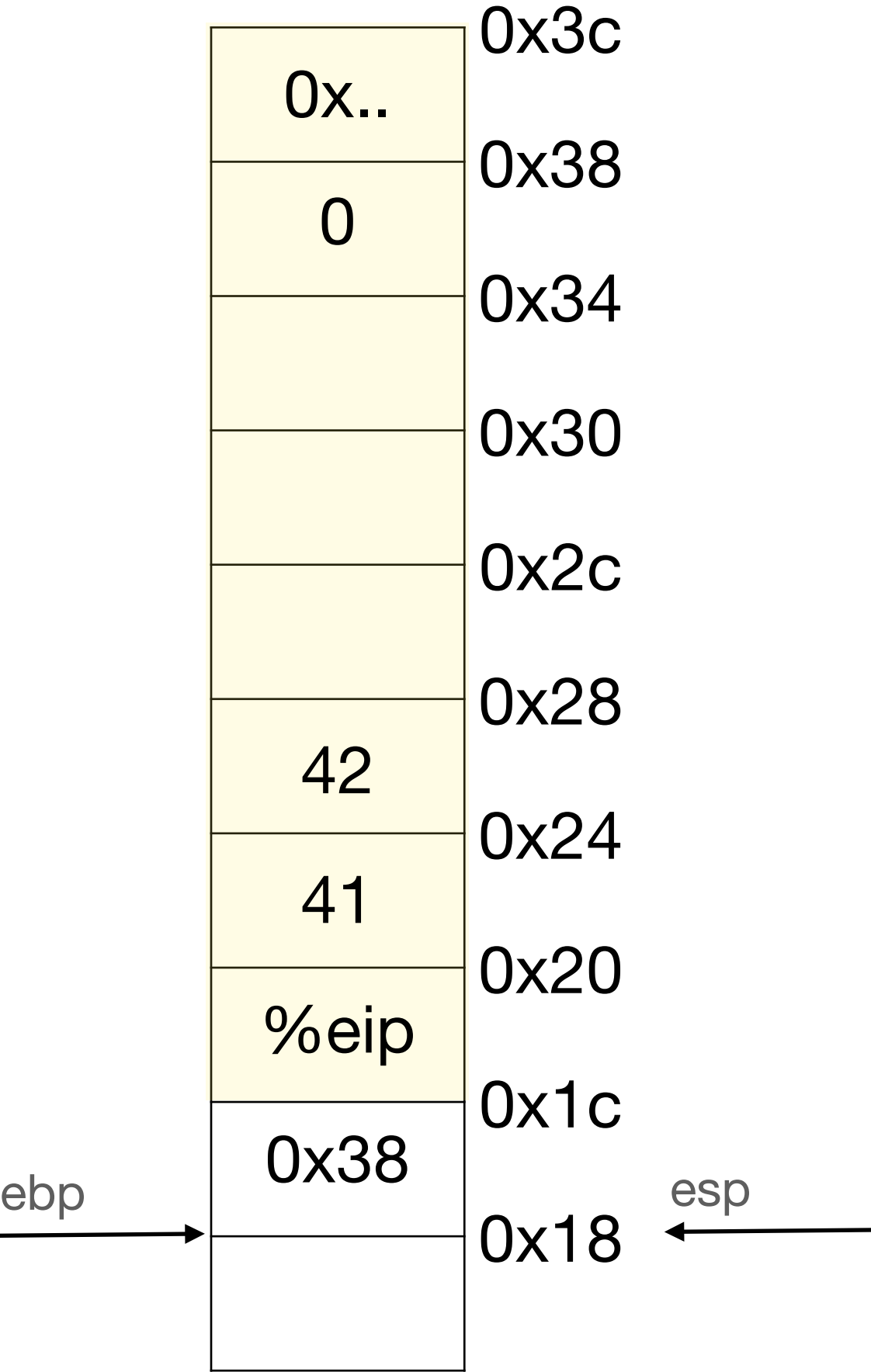
```
_foo:
    pushl %ebp
    movl  %esp, %ebp
    movl  8(%ebp), %eax
    addl  12(%ebp), %eax
    popl  %ebp
    retl

    .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
```

```
Save caller's base pointer
ebp = esp
eax = *(ebp + 8)
eax = eax + *(ebp + 12)
Restore caller's base pointer
change eip to return address

## -- Begin function main

Save caller's base pointer
ebp = esp
esp = esp - 0x18
*(ebp-4)=0
*(esp) = 41
*(esp+4) = 42
Push current eip on to stack, jump to foo
esp = esp + 24 (Restore caller's esp)
Restore caller's ebp
```



Function calling in action: Stack

02.s

eip

→

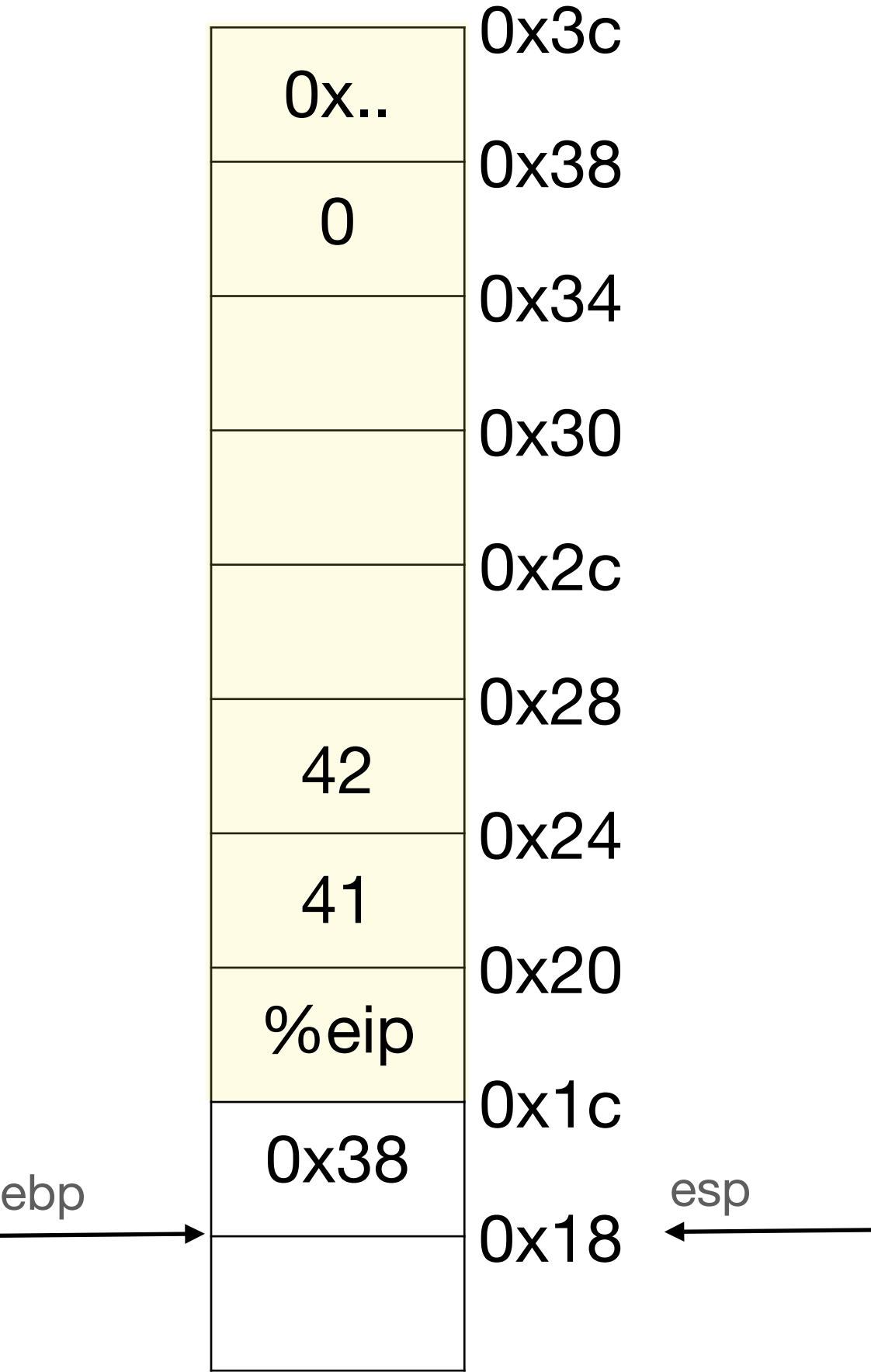
```
_foo:
    pushl %ebp
    movl  %esp, %ebp
    movl  8(%ebp), %eax
    addl  12(%ebp), %eax
    popl  %ebp
    retl

    .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
```

```
Save caller's base pointer
ebp = esp
eax = *(ebp + 8)
eax = eax + *(ebp + 12)
Restore caller's base pointer
change eip to return address

## -- Begin function main

Save caller's base pointer
ebp = esp
esp = esp - 0x18
*(ebp-4)=0
*(esp) = 41
*(esp+4) = 42
Push current eip on to stack, jump to foo
esp = esp + 24 (Restore caller's esp)
Restore caller's ebp
```



Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

0x3c	0x..
0x38	0
0x34	
0x30	
0x2c	
0x28	42
0x24	41
0x20	%eip
0x1c	0x38
0x18	

ebp → 0x38 ← esp

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

	0x3c
0x..	0x3c
0	0x38
	0x34
	0x30
	0x2c
42	0x28
41	0x24
%eip	0x20
0x38	0x1c
	0x18

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

	0x3c
0x..	
0	0x38
	0x34
	0x30
	0x2c
42	0x28
41	0x24
%eip	0x20
0x38	0x1c ← esp
	0x18

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

	0x3c
0x..	0x38
0	0x34
	0x30
	0x2c
	0x28
42	0x24
41	0x20
%eip	0x1c
0x38	0x18

Function calling in action: Stack

02.s

eip

→

```
_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
```

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

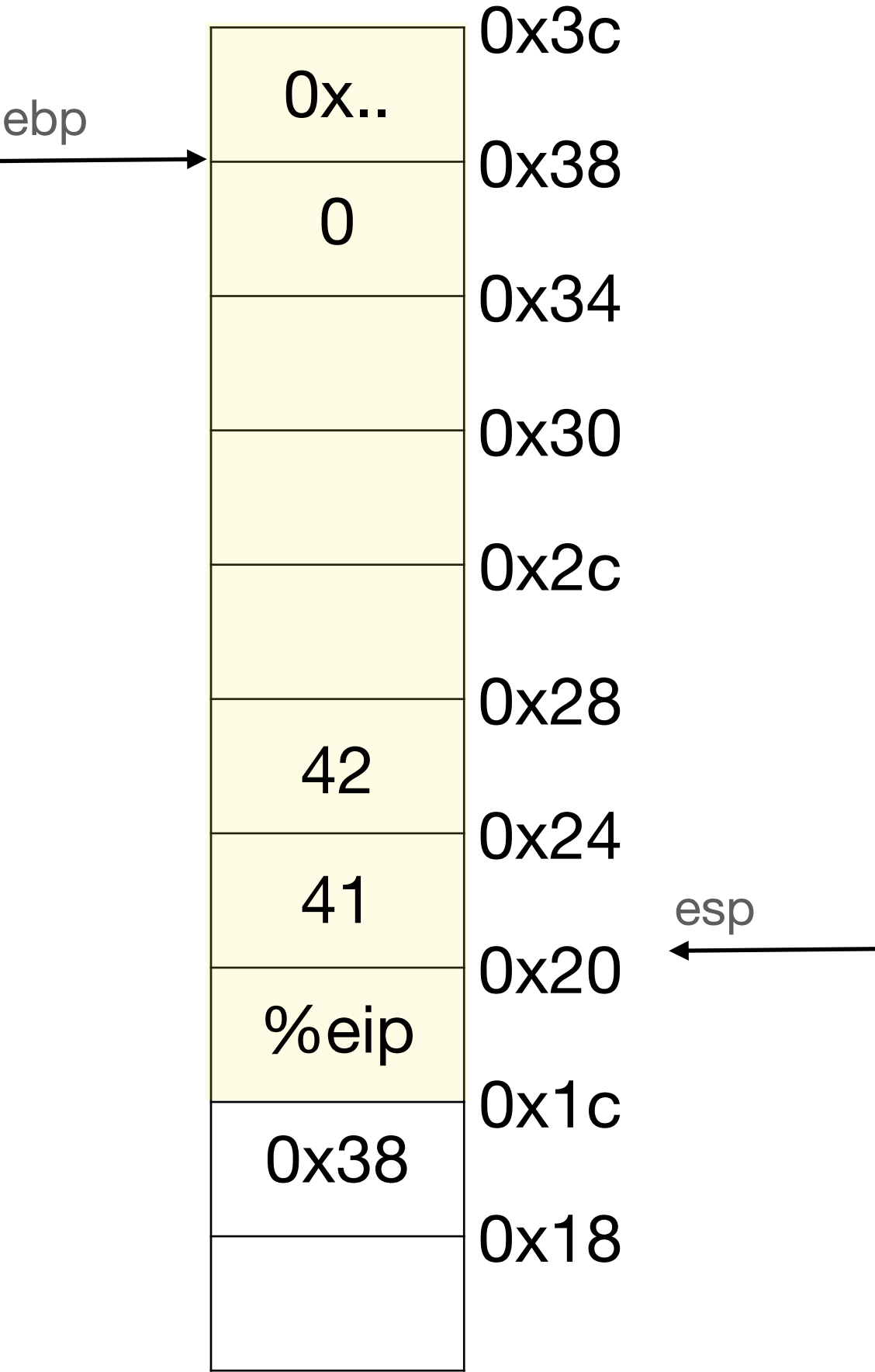
*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp



Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

	0x3c
0x..	
0	0x38
	0x34
	0x30
	0x2c
	0x28
42	
41	0x24
%eip	0x20 ← esp
0x38	0x1c
	0x18

Function calling in action: Stack

02.s

eip

→

calll _foo

addl \$24, %esp

popl %ebp

retl

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

	0x3c
ebp →	0x38
	0x34
	0x30
	0x2c
	0x28
	0x24
	0x20 ← esp
	0x1c
	0x18

Function calling in action: Stack

02.s

eip

→

calll _foo

addl \$24, %esp

popl %ebp

retl

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

	0x3c
ebp →	0x..
	0x38 ← esp
	0
	0x34
	0x30
	0x2c
	0x28
	42
	0x24
	41
	0x20
	%eip
	0x1c
	0x38
	0x18

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

	0x3c
ebp →	0x..
	0x38
	0
	0x34
	0x30
	0x2c
	0x28
	42
	0x24
	41
	0x20
	%eip
	0x1c
	0x38
	0x18

Function calling in action: Stack

02.s

eip

→

_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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

0x..	0x3c
0	0x38 ← esp
	0x34
	0x30
	0x2c
42	0x28
41	0x24
%eip	0x20
0x38	0x1c
	0x18

Function calling in action: Stack

ebp →

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

Save caller's base pointer

ebp = esp

eax = *(ebp + 8)

eax = eax + *(ebp + 12)

Restore caller's base pointer

change eip to return address

-- Begin function main

Save caller's base pointer

ebp = esp

esp = esp - 0x18

*(ebp-4)=0

*(esp) = 41

*(esp+4) = 42

Push current eip on to stack, jump to foo

esp = esp + 24 (Restore caller's esp)

Restore caller's ebp

eip →

esp ←

0x..	0x3c
0	0x38
	0x34
	0x30
	0x2c
	0x28
42	0x24
41	0x20
%eip	0x1c
0x38	0x18

Function calling in action: Stack

ebp →

```
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 →

	0x3c	← esp
0x..	0x38	
0	0x34	
	0x30	
	0x2c	
	0x28	
42	0x24	
41	0x20	
%eip	0x1c	
0x38	0x18	

gcc calling convention

gcc calling convention

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

gcc calling convention

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

- %eip points at first instruction of function

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address

gcc calling convention

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

- `%eip` points at first instruction of function
- `%esp` points at return address
- `%esp+4` points at first argument

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address
- %esp+4 points at first argument

after ret instruction:

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address
- %esp+4 points at first argument

after ret instruction:

- %eip contains return address

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address
- %esp+4 points at first argument

after ret instruction:

- %eip contains return address
- %esp points at arguments pushed by caller

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address
- %esp+4 points at first argument

after ret instruction:

- %eip contains return address
- %esp points at arguments pushed by caller

called function may have trashed arguments

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address
- %esp+4 points at first argument

after ret instruction:

- %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)

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address
- %esp+4 points at first argument

after ret instruction:

- %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)

gcc calling convention

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

- %eip points at first instruction of function
- %esp points at return address
- %esp+4 points at first argument

after ret instruction:

- %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)

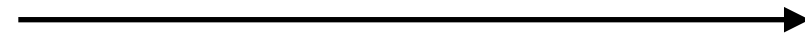
Instructions are in memory!

02.s

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

41 = 0x 00 00 00 29

* fake instructions
call saves eip of next instruction

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

41 = 0x 00 00 00 29
42 = 0x 00 00 00 2a

* fake instructions
call saves eip of next instruction

Instructions are in memory!

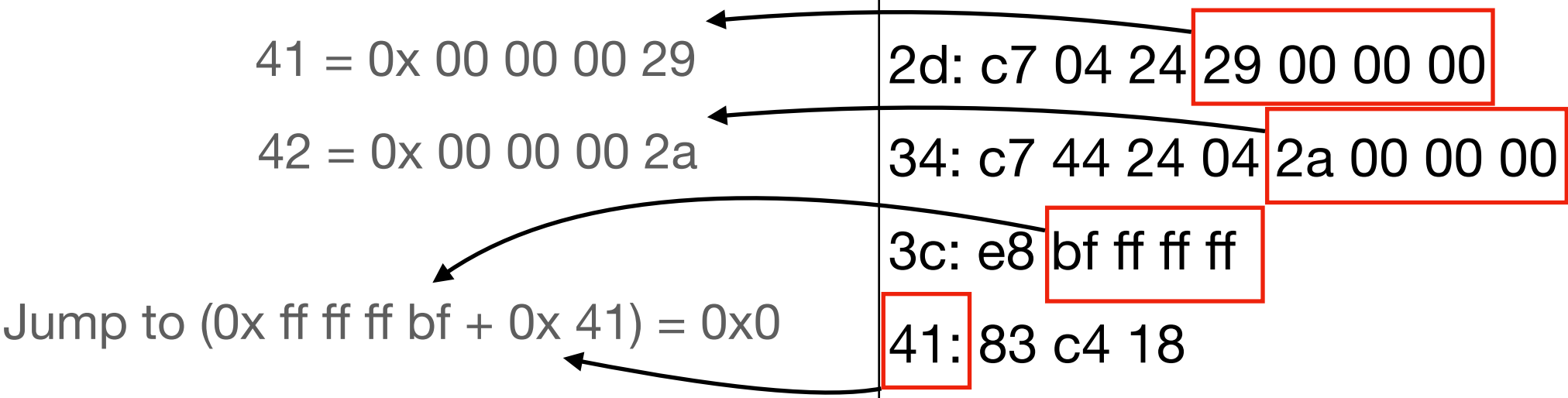
```
02.s

_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

Compiling, linking, loading

Compiling, linking, loading

- *Preprocessor* takes C source code (ASCII text), expands #include etc, produces C source code

Compiling, linking, loading

- *Preprocessor* takes C source code (ASCII text), expands #include etc, produces C source code
- *Compiler* takes C source code (ASCII text), produces assembly language (also ASCII text) *02.main.c -> 02.main.s*

Compiling, linking, loading

- *Preprocessor* takes C source code (ASCII text), expands #include etc, produces C source code
- *Compiler* takes C source code (ASCII text), produces assembly language (also ASCII text) *02.main.c -> 02.main.s*
- *Assembler* takes assembly language (ASCII text), produces *.o file* (binary, machine-readable!) *02.main.s -> 02.main.o*

Compiling, linking, loading

- *Preprocessor* takes C source code (ASCII text), expands #include etc, produces C source code
- *Compiler* takes C source code (ASCII text), produces assembly language (also ASCII text) *02.main.c -> 02.main.s*
- *Assembler* takes assembly language (ASCII text), produces *.o file* (binary, machine-readable!) *02.main.s -> 02.main.o*
- *Linker* takes multiple *‘.o’s*, produces a single *program image a.out* (binary) *02.main.o, 02.func.o -> 02.main*

Compiling, linking, loading

- *Preprocessor* takes C source code (ASCII text), expands #include etc, produces C source code
- *Compiler* takes C source code (ASCII text), produces assembly language (also ASCII text) *02.main.c -> 02.main.s*
- *Assembler* takes assembly language (ASCII text), produces *.o file* (binary, machine-readable!) *02.main.s -> 02.main.o*
- *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

Registers in action

- threads.c
- threads.s, threads.pseudo.c
- threads-notv.c
- threads-notv.s, threads-notv.pseudo.c

Registers in action

- threads.c
 - threads.s, threads.pseudo.c
- threads-notv.c
 - threads-notv.s, threads-notv.pseudo.c

Thread 1	Thread 2
Read counter = 0	
....	
	Read counter = 0

....	

Writer counter = 100000	

	Writer counter = 100000

Registers in action

- threads.c
- threads.s, threads.pseudo.c

Thread 1	Thread 2
Read counter = 0	
Write counter = 1	
	Read counter = 1
	Writer counter = 2
Read counter = 2	
	Read counter = 2
Writer counter = 3	
	Writer counter = 3
	...

- threads-notv.c
- threads-notv.s, threads-notv.pseudo.c

Thread 1	Thread 2
Read counter = 0	
....	
	Read counter = 0

....	

Writer counter = 100000	

	Writer counter = 100000

Memory access hierarchy: caches

Memory access hierarchy: caches

- Registers are limited in size.

Memory access hierarchy: caches

- Registers are limited in size.
- Main memory is slow.

Memory access hierarchy: caches

- Registers are limited in size.
- Main memory is slow.
- Recently accessed data lives on on-chip caches.

Memory access hierarchy: caches

- Registers are limited in size.
- Main memory is slow.
- Recently accessed data lives on on-chip caches.
- Mostly transparent to OS

Memory access hierarchy: caches

- Registers are limited in size.
- Main memory is slow.
- Recently accessed data lives on on-chip caches.
- Mostly transparent to OS

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 numbers 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

I/O devices

Port-mapped IO

- Similar to reading from (writing to) memory locations

I/O devices

Port-mapped IO

- Similar to reading from (writing to) memory locations
- Special instructions:

I/O devices

Port-mapped IO

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

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

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`

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`

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

```
#define DATA_PORT    0x378
```

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

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

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

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


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

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

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

```
#define DATA_PORT    0x378
#define STATUS_PORT   0x379
#define CONTROL_PORT  0x37A
#define    BUSY 0x80
#define    STROBE 0x01
```

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

```
#define DATA_PORT    0x378
#define STATUS_PORT   0x379
#define CONTROL_PORT  0x37A
#define    BUSY 0x80
#define    STROBE 0x01
void
```

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

```
#define DATA_PORT    0x378
#define STATUS_PORT   0x379
#define CONTROL_PORT  0x37A
#define    BUSY 0x80
#define    STROBE 0x01
void
lpt_putc(char c)
```

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

```
#define DATA_PORT    0x378
#define STATUS_PORT   0x379
#define CONTROL_PORT  0x37A
#define    BUSY 0x80
#define    STROBE 0x01
void
lpt_putc(char c)
{
```

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

```
#define DATA_PORT    0x378
#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 */
```

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

```
#define DATA_PORT    0x378
#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

```
#define DATA_PORT    0x378
#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

```
#define DATA_PORT    0x378
#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);

    /* put the byte on the data lines */
```

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

```
#define DATA_PORT    0x378
#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);

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

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

```
#define DATA_PORT    0x378
#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);

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

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

```
#define DATA_PORT    0x378
#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);

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

    /* tell the printer to look at the data */
```

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

```
#define DATA_PORT    0x378
#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);

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

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

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

```
#define DATA_PORT    0x378
#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);

    /* 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

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

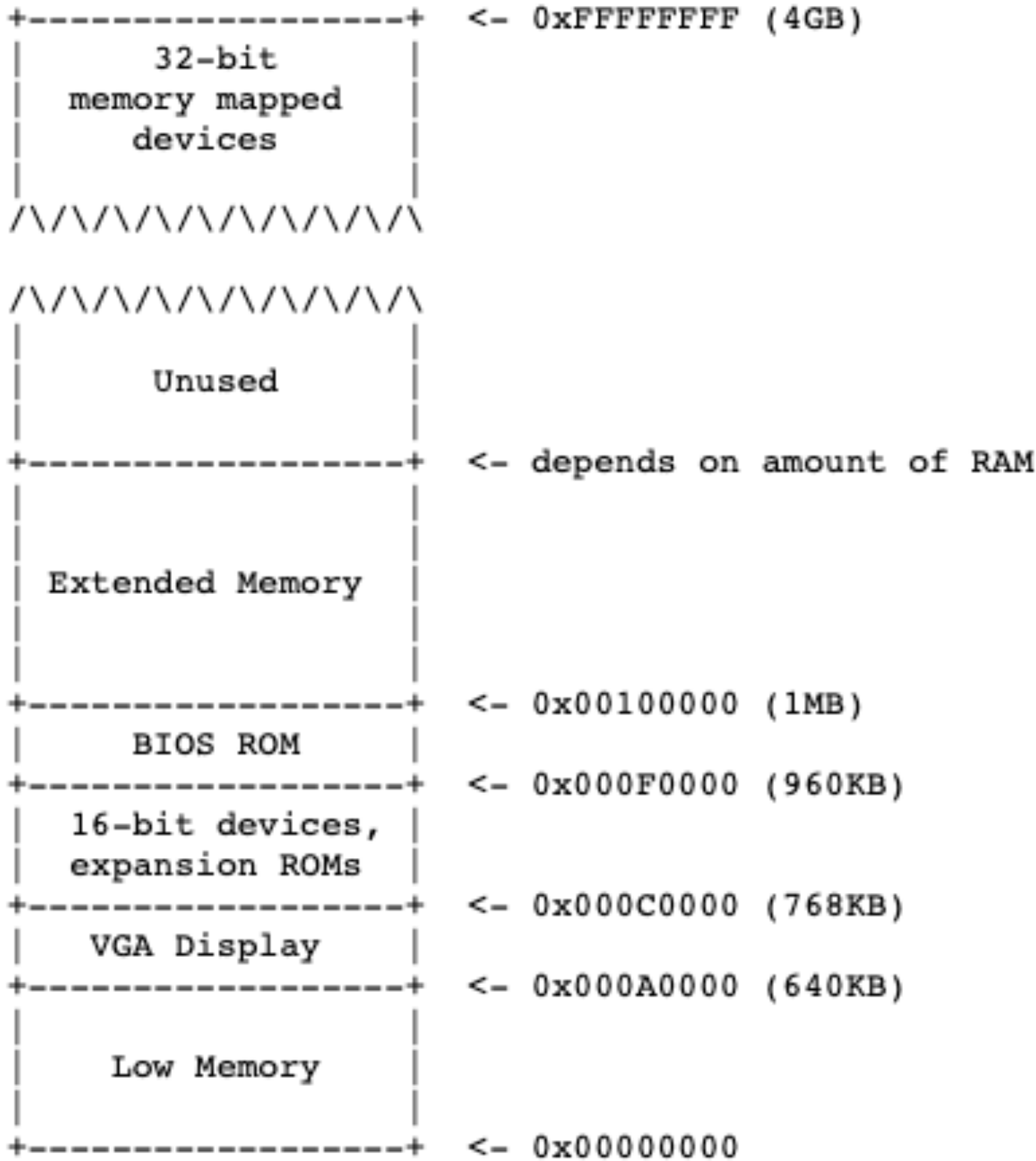
```
#define DATA_PORT    0x378
#define STATUS_PORT   0x379
#define CONTROL_PORT  0x37A
#define    BUSY 0x80
#define    STROBE 0x01
void
lpt_putc(char c)
{
    /* wait for printer to consume previous byte */
    while((inb(STATUS_PORT) & BUSY) == 0);

    /* 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

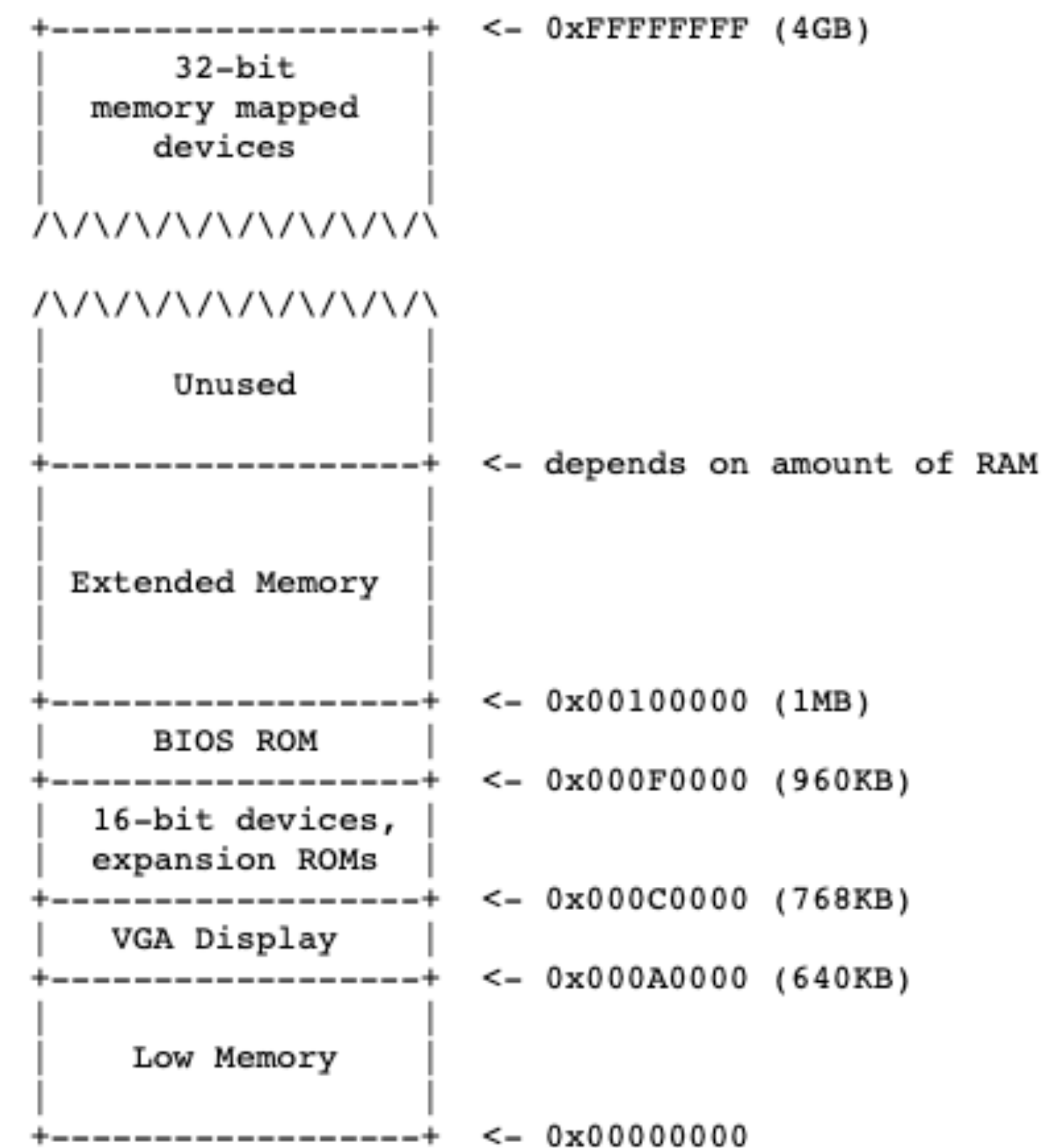
Memory-mapped IO



I/O devices

Memory-mapped IO

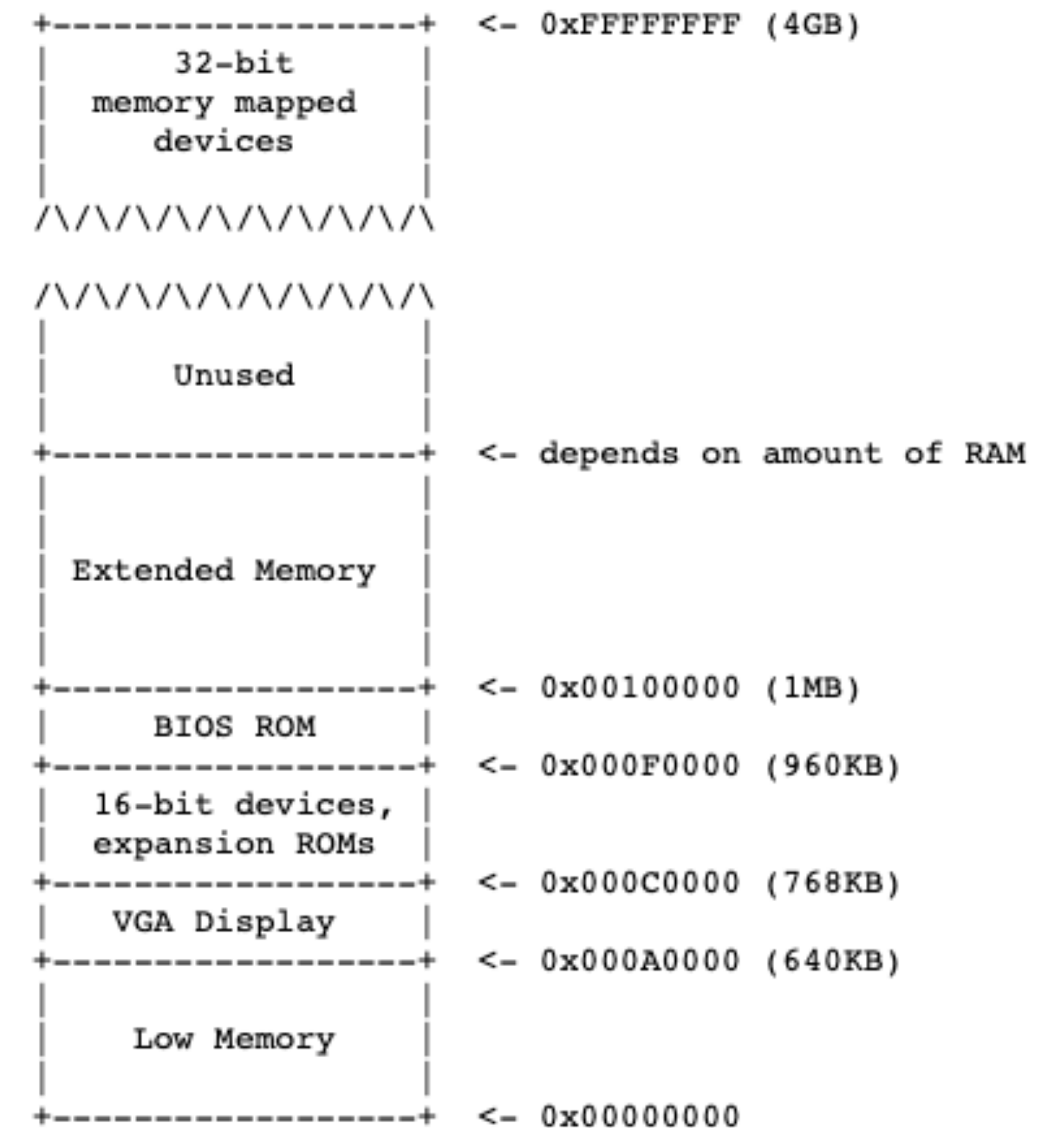
- Regular memory access instructions



I/O devices

Memory-mapped IO

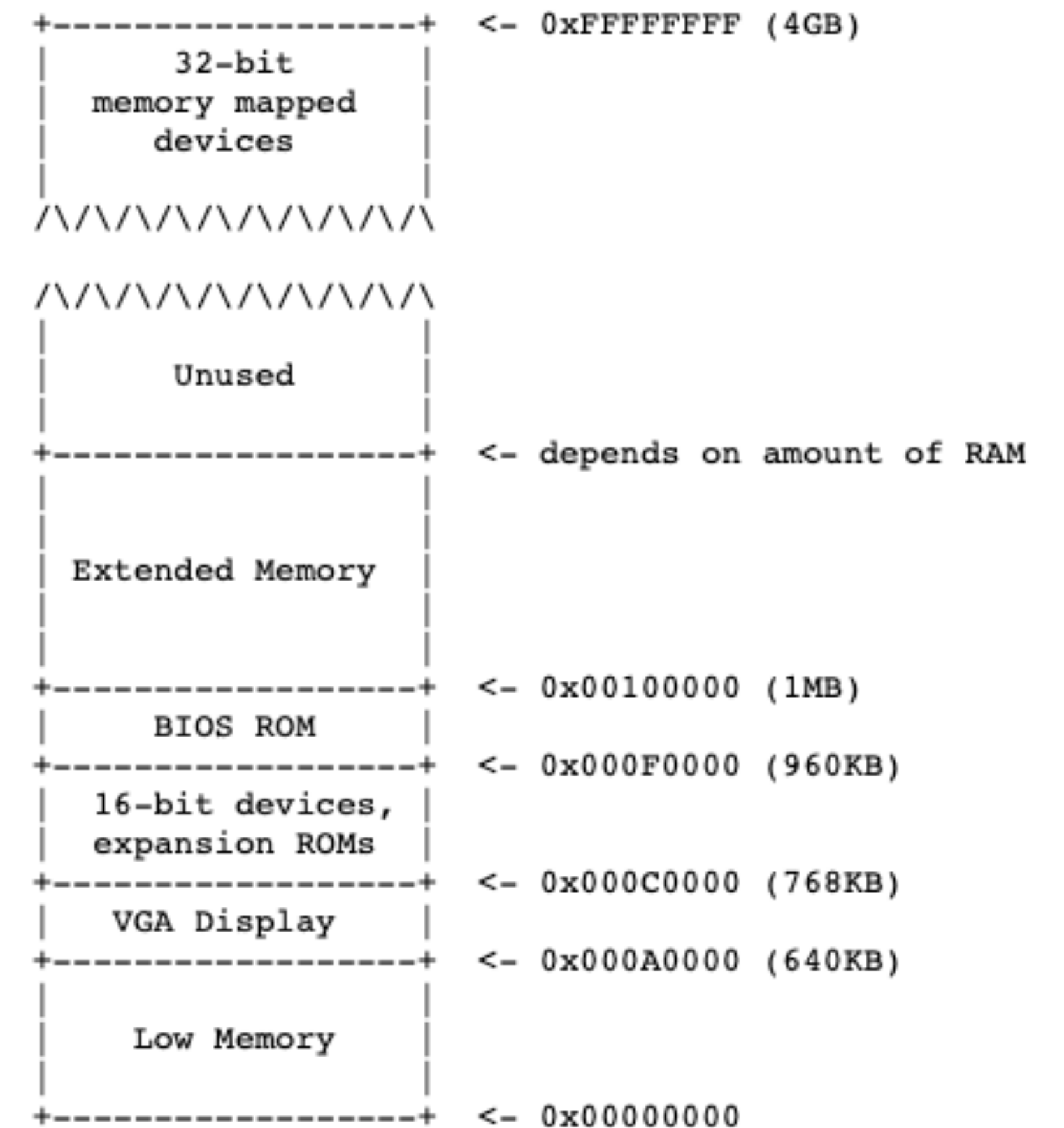
- Regular memory access instructions
- Reads and writes are routed to appropriate device



I/O devices

Memory-mapped IO

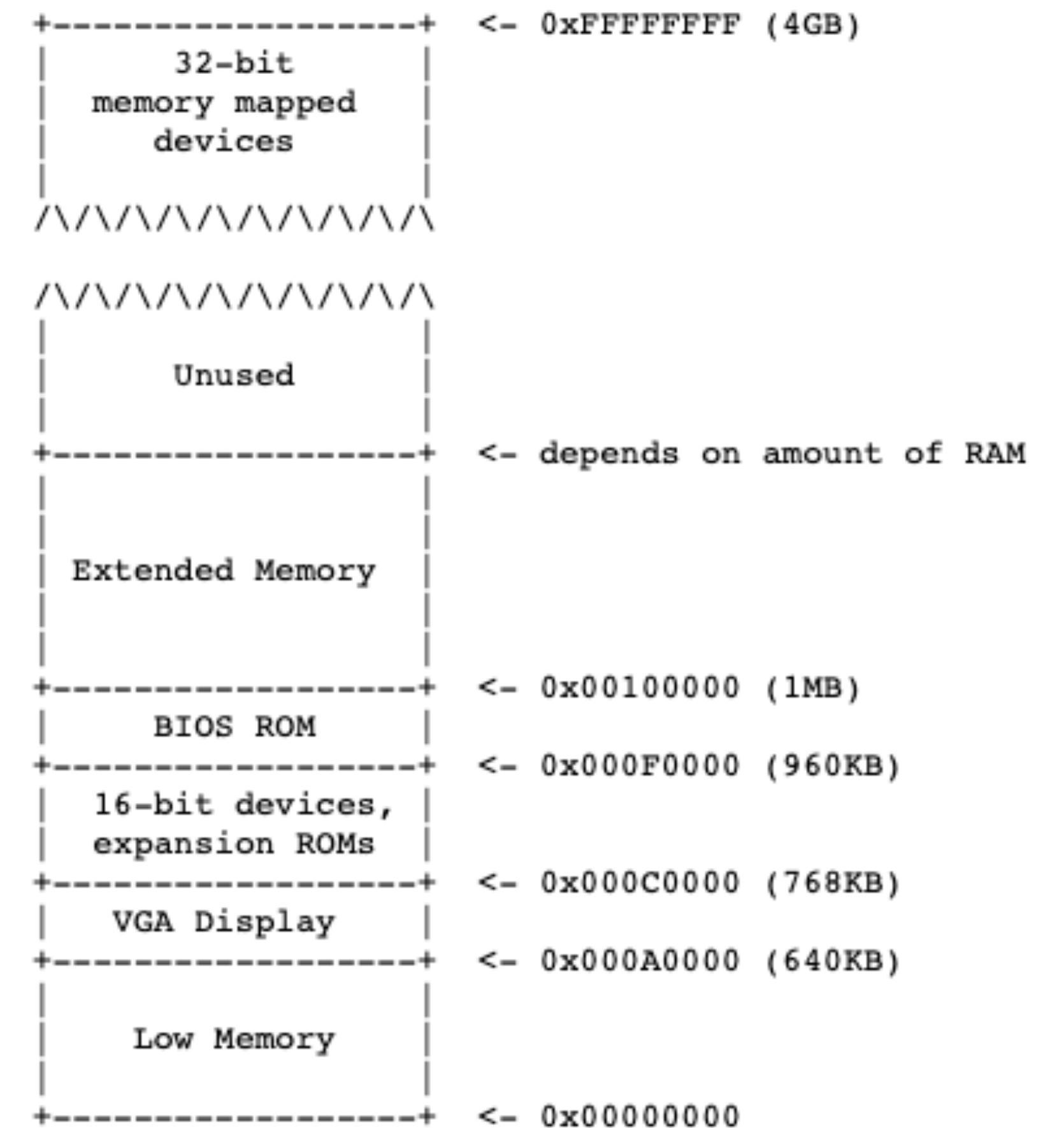
- Regular memory access instructions
- Reads and writes are routed to appropriate device
 - Writes to VGA memory appear on the screen



I/O devices

Memory-mapped IO

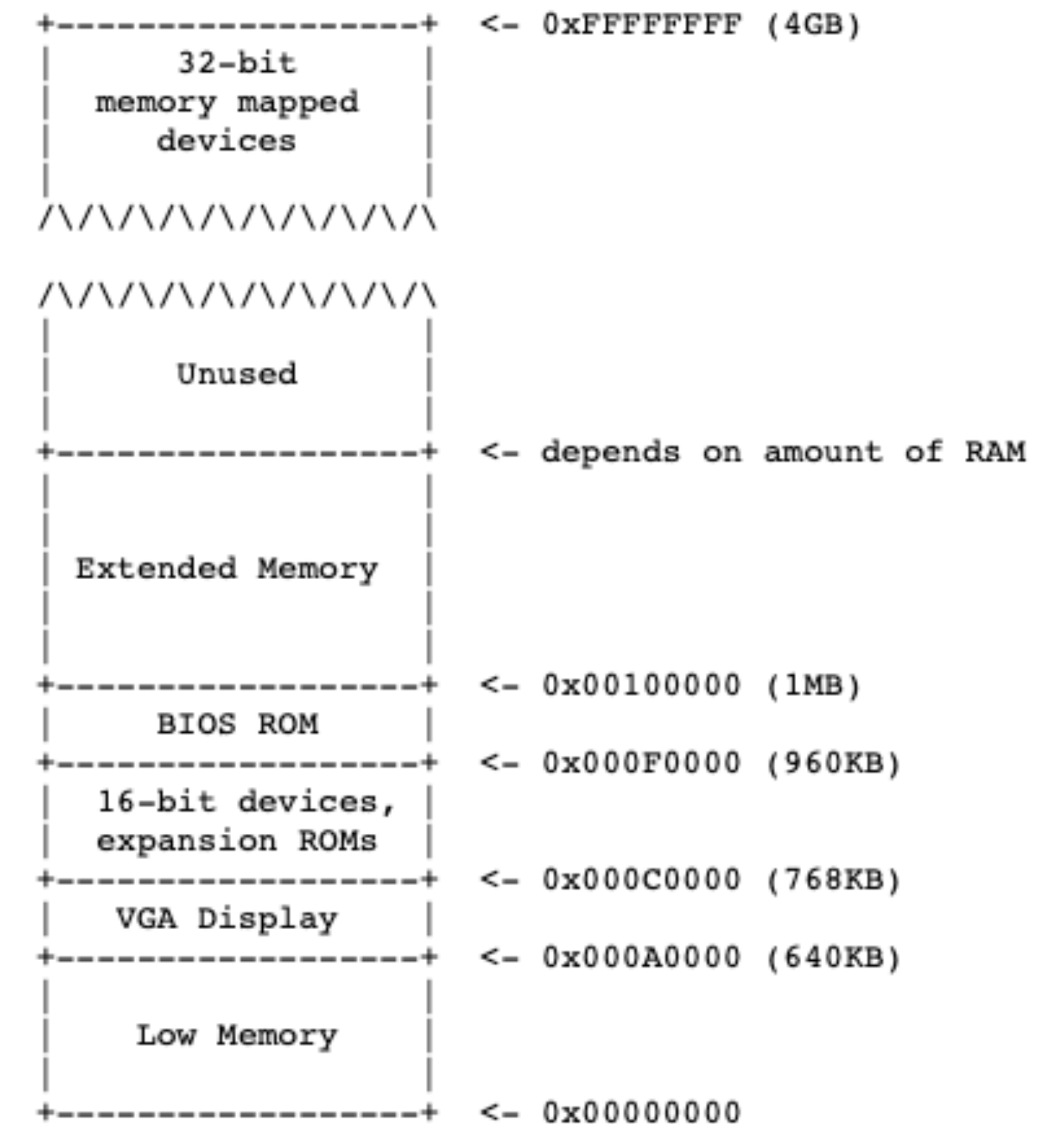
- Regular memory access instructions
- Reads and writes are routed to appropriate device
 - Writes to VGA memory appear on the screen
- Power-on jumps %eip to 0x000F0000



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!



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

