Introduction to Computer Organization

DIS 1H – WEEK 2

Slides adapted from Eric Kim

Today's Schedule

- x86 Organization
- x86 Assembly
- Lecture material review

Fun with C Puzzles

Integer C Puzzles

Initialization

```
int x = foo();
int y = bar();
unsigned ux = x;
unsigned uy = y;
```

- `x < 0` `->` `((x*2) < 0)`
- `ux >= 0`
- `x & 7 == 7` `->` `(x<<30) < 0`
- `ux > -1`
- `x > y` `->` `-x < -y`
- `x * x >= 0`
- `x > 0 && y > 0` `->` `x + y > 0`
- `x >= 0` `->` `-x <= 0`
- `x <= 0` `->` `-x >= 0`

Fun with C Puzzles - Answers

- Assume machine with 32 bit word size, two's comp. integers
- TMin makes a good counterexample in many cases

❑ `x < 0`	⇒	`((x*2) < 0)`	**False:**	*TMin*
❑ `ux >= 0`			**True:**	0 = *UMin*
❑ `x & 7 == 7`	⇒	`(x<<30) < 0`	**True:**	$x_1 = 1$
❑ `ux > -1`			**False:**	0
❑ `x > y`	⇒	`-x < -y`	**False:**	`-1`, *TMin*
❑ `x * x >= 0`			**False:**	`30426`
❑ `x > 0 && y > 0`	⇒	`x + y > 0`	**False:**	*TMax*, *TMax*
❑ `x >= 0`	⇒	`-x <= 0`	**True:**	–*TMax* < 0
❑ `x <= 0`	⇒	`-x >= 0`	**False:**	*TMin*

x86 Organization

● The basic abstraction of memory that is taught in CS 31 and CS 32 is that data is stored in memory.

● For example, if you have a 32-bit addressable space, then the addresses that are in memory range from 0x00000000 to 0xFFFFFFFF(2^{31}-1).

● It's not like you'll ever see a variable that you can't dereference in C. Therefore variables must always be stored in memory, right?

x86 Organization

● The variables will be stored in memory, which is a physical construct (RAM).

● However, RAM is too slow to keep up with the demands of a processor.

● Accessing RAM takes approximately 200 times the amount of time as it takes to execute a standard instruction.

x86 Organization

- Since nearly everything involves doing some operation on a variable, we need some way of accessing memory at a speed that is comparable to the speed that it takes to execute the average instruction.

- We need caches, we need virtual memory, but for now, we'll focus on “registers”.

x86 Organization

● Registers are extremely small physical containers that each store a number of bits.

● A 64-bit addressable machine will have registers that are 64-bits.

● In such a case, each register holds 8 bytes (which is tiny), but the access time is extremely quick.

● When a program needs to work on a piece of data, it will bring it into a register first.

x86 Organization: Registers

- x86-64 contains 16 general purpose registers.
- They are identified by a short name such as (%rax, %rsi, %r8, etc.)
- In the interest of being able to access each register at a finer grain, there are multiple ways of accessing the data within each register.
- Ex. %rax refers to the full 64-bits stored in the register while %eax refers to the lower 32-bits.

x86 Organization: Registers

- _h: upper 8-bits of lower 16-bits
- _l: lower 8-bits
- _x :lower 16-bits.
- e_x : lower 32-bits (e stands for 'extended').
- r_x : full 64-bit register

x86 Organization: Registers

- Registers are very simple containers that store a bit configuration and nothing more.

- If you know that a 64-bit signed long is stored in a register, there is nothing about this register that indicates that the original intention was for this value to be signed.

- The compiler will simply compile machine code that treats the bit vector in the register as if it were a signed value.

x86 Assembly

- AT&T's (also GNU/GAS) x86 notation (the notation that we will use):

  [op] [src] [dst]

- "Fun" fact: Intel's x86 notation:

  [op] [dst] [src]

x86 Assembly

[operation] [source] [destination]

ex.

- movq %rax 4(%rbx)
- addq %rbx %rcx

x86 Assembly: Ops

The mov_ family: move data from the source to the destination. The suffix determines how much data to move.

– movb : move a byte

– movw : move a word (16 bits)

– movq : move a quad word (64 bits)

- movq %rax, %rbx
- movq %rax, (%rbx)

x86 Assembly: Ops

A comment regarding “word” size.

● A “word” is just a label of convenience that is used refer to contiguous bytes of memory of a common size.

● On a 32-bit machine, a word is 4 bytes. On a 64-bit machine, a word is 8 bytes.

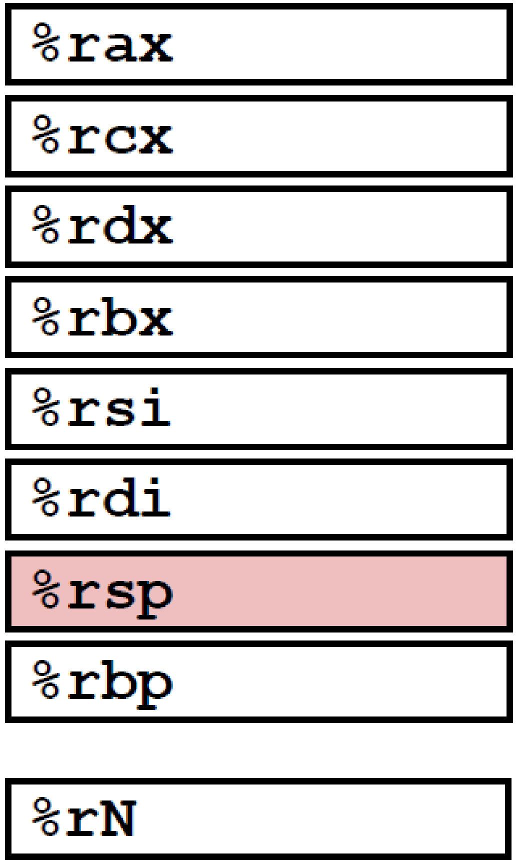
● But back when registers were only 16-bits and x86 was being developed, “words” were 16-bits.

Moving Data

- **Moving Data**

  `movq` ***Source*, *Dest*:**

- **Operand Types**
  - ***Immediate:*** Constant integer data
    - Example: **`$0x400`, `$-533`**
    - Like C constant, but prefixed with **`'$'`**
    - Encoded with 1, 2, or 4 bytes
  - ***Register:*** One of 16 integer registers
    - Example: **`%rax`, `%r13`**
    - But **`%rsp`** reserved for special use
    - Others have special uses for particular instructions
  - ***Memory:*** 8 consecutive bytes of memory at address given by register
    - Simplest example: **`(%rax)`**
    - Various other "address modes"



x86 Assembly: Addressing Modes

- Consider:

– movq %rax, (%rbx) <--- ?

- The parentheses indicate a memory operation.

- That is, the source and destination operands are able to refer to values that are located in memory, rather than just registers.

- The parentheses () means:

– Treat the bit vector within as a memory address.

– Go follow that address into memory and get the value at that address.

x86 Assembly: Addressing Modes

- Say %rax = 0xFEEDABBA and %rbx = 0x80.
- movq %rax, %rbx

– Result: %rax = 0xFEEDABBA, %rbx = 0xFEEDABBA

- movq %rax, (%rbx)

– Result: the value that is located in memory address 0x80 is set as 0xFEEDABBA.

– In a more C-like form, this is essentially:

– MEM[0x80] = 0xFEEDABBA; or

– *(0x80) = 0xFEEDABBA;

x86 Assembly: Addressing Modes

● The '$' symbol prefix indicates an “immediate” which is constant number value.

● If %rax = 0xb1ab

● movl $0xdea1, %rax

– Result: %rax = 0xdea1

x86 Assembly

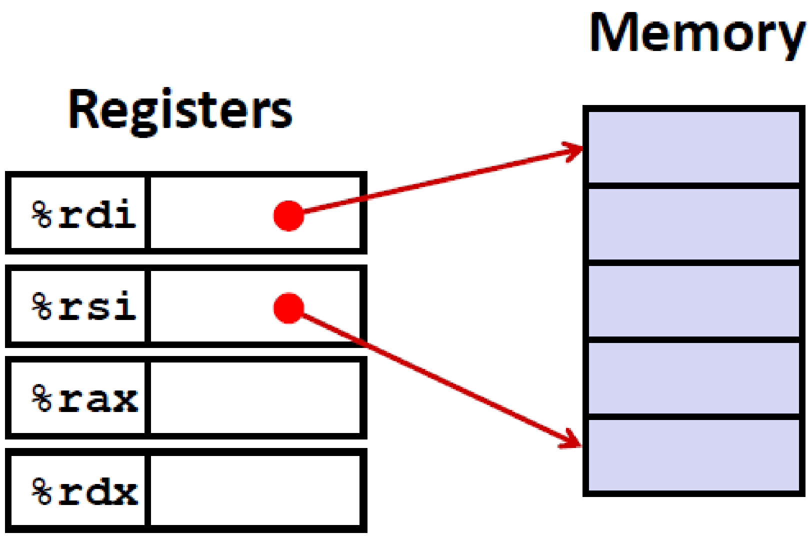
`movq` Operand Combinations

	Source	Dest	Src,Dest	C Analog
`movq`	*Imm*	*Reg*	`movq $0x4,%rax`	`temp = 0x4;`
		Mem	`movq $-147,(%rax)`	`*p = -147;`
	Reg	*Reg*	`movq %rax,%rdx`	`temp2 = temp1;`
		Mem	`movq %rax,(%rdx)`	`*p = temp;`
	Mem	*Reg*	`movq (%rax),%rdx`	`temp = *p;`

Cannot do memory-memory transfer with a single instruction

Understanding Swap()

```
void swap
   (long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```



Register	Value
%rdi	xp
%rsi	yp
%rax	t0
%rdx	t1

```
swap:
   movq    (%rdi), %rax   # t0 = *xp
   movq    (%rsi), %rdx   # t1 = *yp
   movq    %rdx, (%rdi)   # *xp = t1
   movq    %rax, (%rsi)   # *yp = t0
   ret
```

Understanding Swap()

Registers

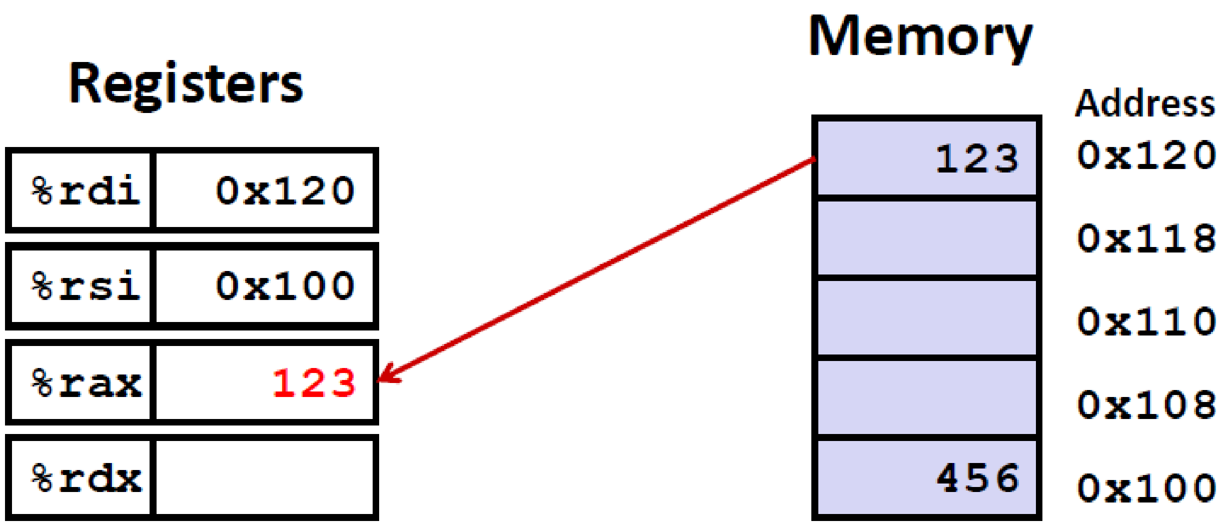
%rdi	0x120
%rsi	0x100
%rax	
%rdx	

Memory

	Address
123	0x120
	0x118
	0x110
	0x108
456	0x100

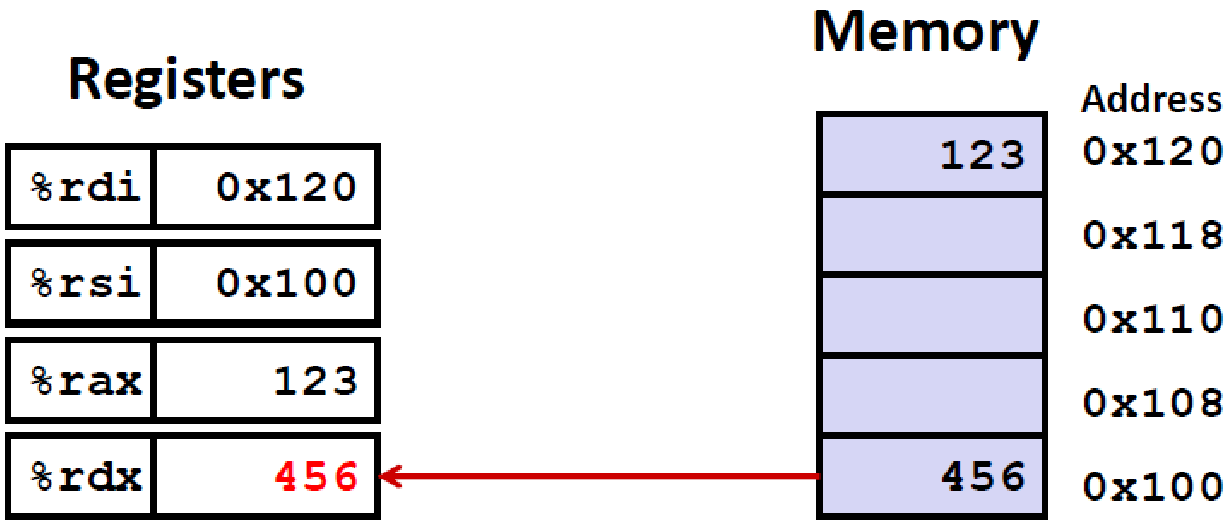
```
swap:
   movq    (%rdi), %rax   # t0 = *xp
   movq    (%rsi), %rdx   # t1 = *yp
   movq    %rdx, (%rdi)   # *xp = t1
   movq    %rax, (%rsi)   # *yp = t0
   ret
```

Understanding Swap()



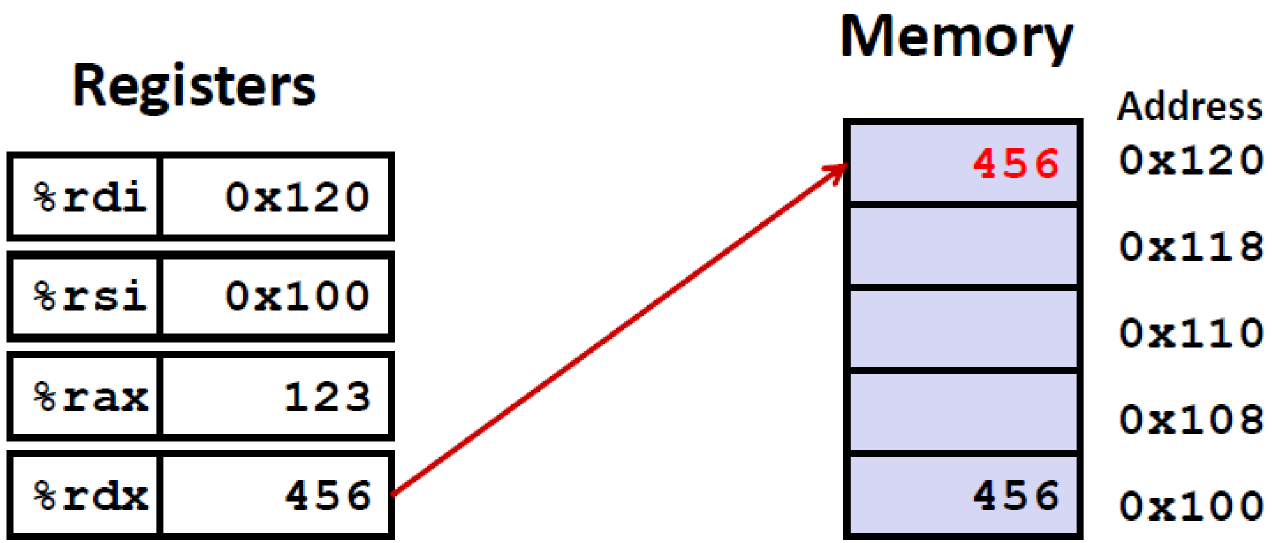

```
swap:
   movq    (%rdi), %rax   # t0 = *xp
   movq    (%rsi), %rdx   # t1 = *yp
   movq    %rdx, (%rdi)   # *xp = t1
   movq    %rax, (%rsi)   # *yp = t0
   ret
```

Understanding Swap()



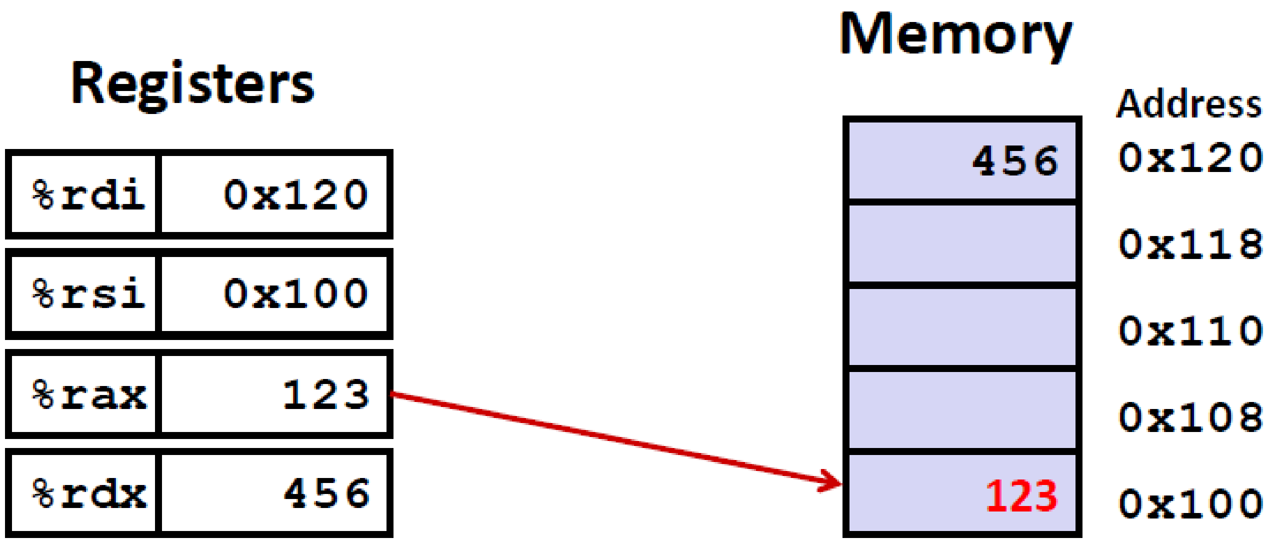

```
swap:
   movq     (%rdi), %rax   # t0 = *xp
   movq     (%rsi), %rdx   # t1 = *yp
   movq     %rdx, (%rdi)   # *xp = t1
   movq     %rax, (%rsi)   # *yp = t0
   ret
```

Understanding Swap()




```
swap:
   movq    (%rdi), %rax   # t0 = *xp
   movq    (%rsi), %rdx   # t1 = *yp
   movq    %rdx, (%rdi)   # *xp = t1
   movq    %rax, (%rsi)   # *yp = t0
   ret
```

Understanding Swap()




```
swap:
   movq    (%rdi), %rax   # t0 = *xp
   movq    (%rsi), %rdx   # t1 = *yp
   movq    %rdx, (%rdi)   # *xp = t1
   movq    %rax, (%rsi)   # *yp = t0
   ret
```

x86 Assembly: Basic Instructions

Other instructions:

- add_ src, dst # dst = dst + src
- sub_ src, dst # dst = dst - src
- neg_ dst #dst = -dst
- not_ dst #dst = ~dst
- sar imm, dst # dst = dst >> imm (shift arithmetic right)
- Etc...

x86 Assembly: Advanced Addressing Modes

- IMM(R1, R2, S) : Scaled and displaced array access.

– Intended usage:

– R1 : Base array address

– R2 : Index into array

– S : Size of array data type in bytes

– IMM : Displacement

- movq A(B, C, D), %rax

– %rax = *(A + B + C*D)

x86 Assembly: Advanced Addressing Modes

● D(R1) : Base + displacement addressing

– If %rax = 0x10.

– movq 8(%rax), %rbx

● Result: %rbx gets the value at memory address 0x10 + 8 = 0x18, *not* the number 0x18

● %rbx = *(%rax + 8).

x86 Assembly: Advanced Addressing Modes

● (,R2,S) : Scaled indexing, s must be 1, 2, 4, or 8.

– If %rax = 0x01 and S = 2.

– movl (, %rax, 2), %rcx

● Result: The value at memory address 0x01 * 2 is saved to %rcx.

● IMM(R1, R2, S) : Scaled and displaced array access.

– If %rax = 0x400, %rbx = 2, S = 2, and D = 20.

– movl 0x20(%rax, %rbx, 2), %rcx

● Result: The value at memory address 0x400 + 0x2*2 + 0x20 is placed in %rcx.

x86 Assembly nuances: mov_

- It is possible to move from a smaller container to a larger container.
- Assume that %dh = 0xCD, %eax = 0x98765432
- movb %dh, %eax

– What's the result?

x86 Assembly nuances: mov_

- It is possible to move from a smaller container to a larger container.
- Assume that %dh = 0xCD, %eax = 0x98765432
- movb %dh, %eax

– What's the result? It's not allowed (suffix mismatch).

The destination has a 32-bit length while the mov**b** expects only to move a byte.

- movb %dh, %al

– Result: %eax = 0x987654CD

x86 Assembly nuances: mov_

- movsXY : move and sign extend from size X to size Y.

– Ex: movsbl : move a byte from the source and sign extend it to a long (4 bytes)

- movzXY : move and zero extend from size X to size Y.

– Ex: movzbw : move a byte from the source and zero extend it to a word (2 bytes)

x86 Assembly nuances: mov_

- %dh = 0xCD, %eax = 0x98765432
- movsbl %dh, %eax

– Result: %eax = 0xFFFFFFCD

- movzbl %dh, %eax

– Result: %eax = 0x000000CD

- movzbw %dh, %eax?

– Result: Not allowed. Sign extending to w (16-bits) but to %eax (32-bit container).

x86 Assembly nuances: mov_

- As a final note about mov, the size of the prefix must match the operands. You cannot have:

– movl %ax, (%esp) // Can't move a 32-bit quantity from a 16-bit register

– movl %eax, %dx // Can't move a 32-bit quantity into a 16-bit register.

x86 Assembly nuances: mov_

Additionally memory references match all sizes:

– movb %al, (%rbx)

– movw %ax, (%rbx)

– movq %rax, (%rbx)

– All allowed. The data will be moved to memory starting at that address based on the data type size

x86 Assembly nuances

- Certain operations are expected to work with data types that are larger than a single register can contain.
- Consider the x86-64 case. We have 64-bit registers, but in order to store a 128-bit value, we can use two registers.
- Ex: %rdx contains the upper 64-bits of the value, %rax contains the lower 64-bits of the value.
- Value = %rdx : %rax, the colon means concatenation.

x86 Assembly nuances

● imulq S :

– The register %rdx contains the upper half of R[%rax] * S.

– The register %rax contains the lower half of R[%rax] * S.

● idivq S

– %rax contains the quotient of R[%rdx]:R[%rax]/S

– %rdx contains the remainder of R[%rdx]:R[%rax]/S

● Note: none of these instructions technically specified %rax or %rdx. mulq and divq are single operand. By convention %rax and %rdx are the registers that are used in this case.

x86 Assembly: Some Context

x86 Assembly: Some Context

● Hopefully at this point, the basics of assembly are clear. That is, if you see a snippet of assembly, you should be able to describe the operations that are happening.

● Now, let's establish some context as to how a program is run.

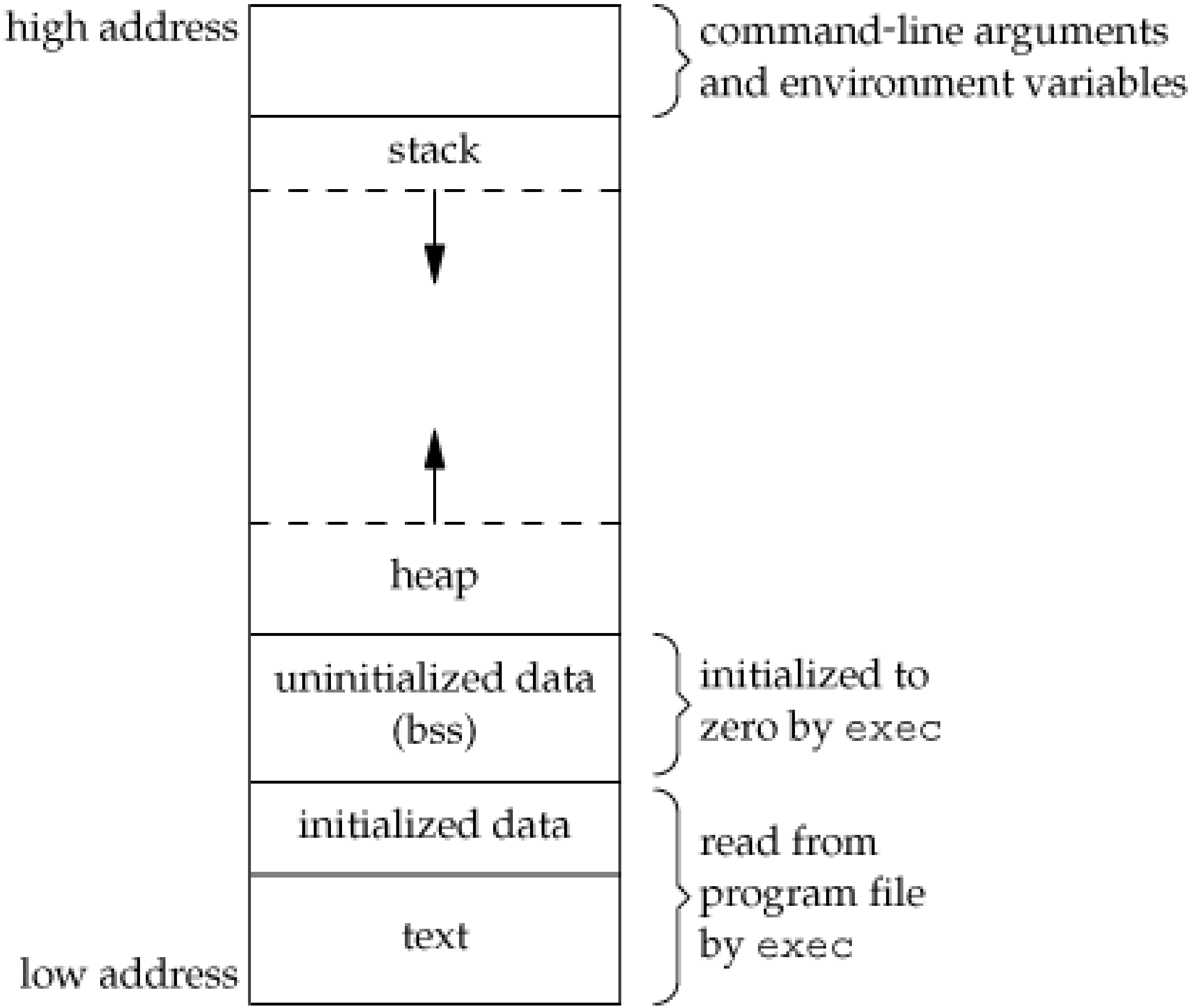
● Namely, memory

x86 Assembly: Some Context

- What we know:

– Data is stored in memory (and in registers when we need to operate on them)

- int i = 100;
- If you do &i, you may get something like 0x7FFF4980, which is it's address in memory.
- This treats memory as if it were a single construct when in fact, it can be subdivided further.


high address
low address
command-line arguments
and environment variables
stack
heap
uninitialized data
(bss)
initialized to
zero by exec
initialized data
text
read from
program file
by exec

x86 Assembly: Some Context

- The main reason I brought this up:
- The program code is stored in memory. So how does the processor keep track of where it is executing?
- Naturally, with a pointer that points to the instructions location in memory.

x86 Assembly: Some Context

- This pointer is stored in register %eip (in 32-bit) or %rip (in 64-bit).

- “ip” stands for instruction pointer.

- This register simply contains the address of the instruction that is to be executed (note: not the instruction itself).

Function Frames

-When a function is called, a section of the stack is set aside for the function.

-Represented by two registers: the base pointer (%ebp) and the stack pointer (%esp).

%ebp: base pointer

-Points to the "beginning" of the function's stack frame.

-Should not change during function execution, unless another function call is made.

%ebp: Accessing Arguments

- Suppose f() calls g(x,y). Then, g can access its arguments x,y via %ebp:
    - x is at 8(%ebp), and y is at 12(%ebp)

%ebp

- What's at 0(%ebp) and 4(%ebp)?
- %ebp points to the saved %ebp, ie the f's base pointer.
- Need to set %ebp to the f's %ebp before returning from g! More on this later.

%ebp

- 4(%ebp) points to the saved return address, i.e. the next instruction to execute after returning from the function.
- The command `ret` updates the %eip (Instruction Pointer)

%esp: Stack Pointer

-Points to the "end" of the function frame.

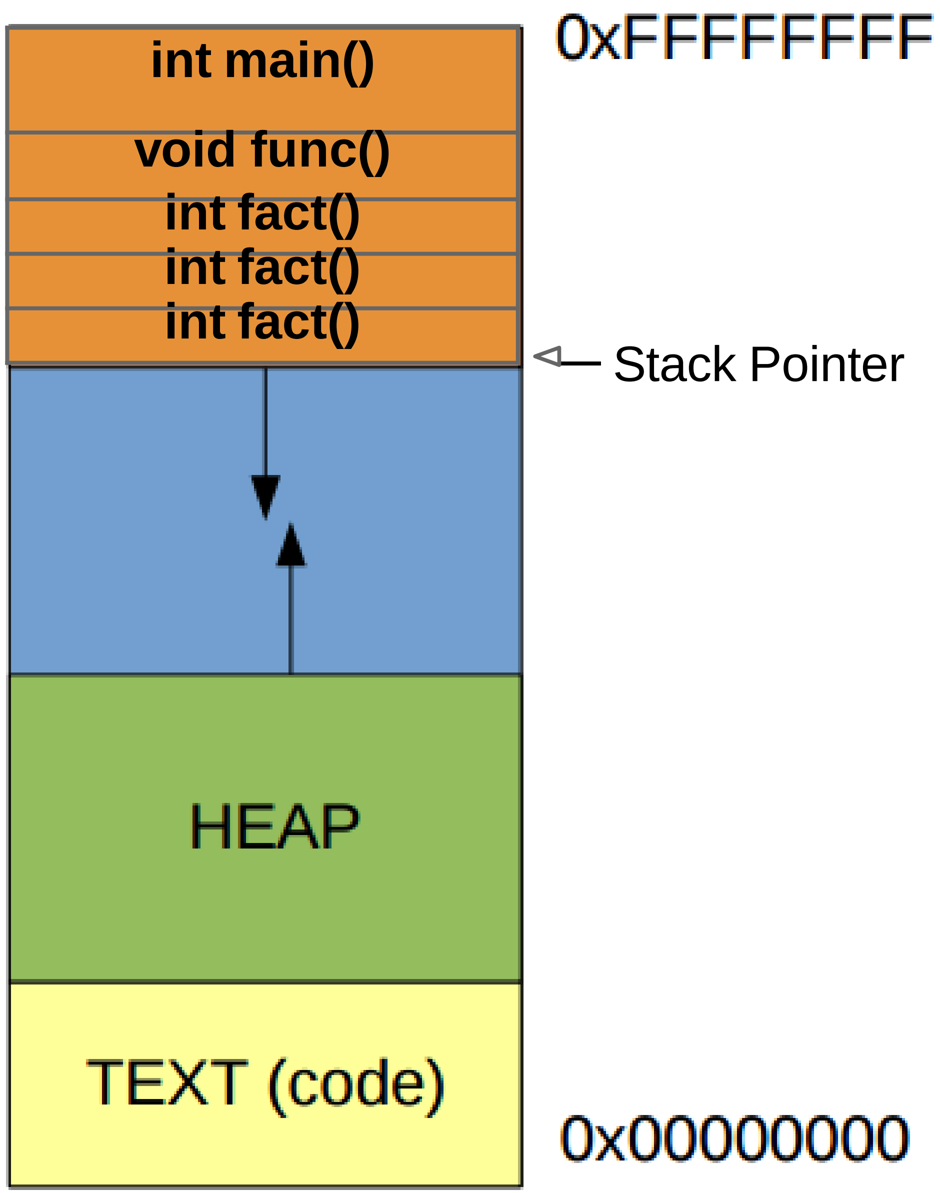
-All of a function's local variables are stored between %ebp and %esp

%esp - Static Allocation

- At the start of a function, we allocate all required storage of local/temp variables by updating %esp

The Stack

- Contains local variables
- LIFO
- Grows “downward”
- Organized in frames



The Stack: pushl and popl

- pushl <SRC>
  - subl $4, %esp
  - movl <SRC> (%esp)
- popl <DST>
  - movl (%esp) <DST>
  - addl $4 %esp

pushl, popl are convenience commands. Could simply use subl, movl,addl, etc.

The Stack

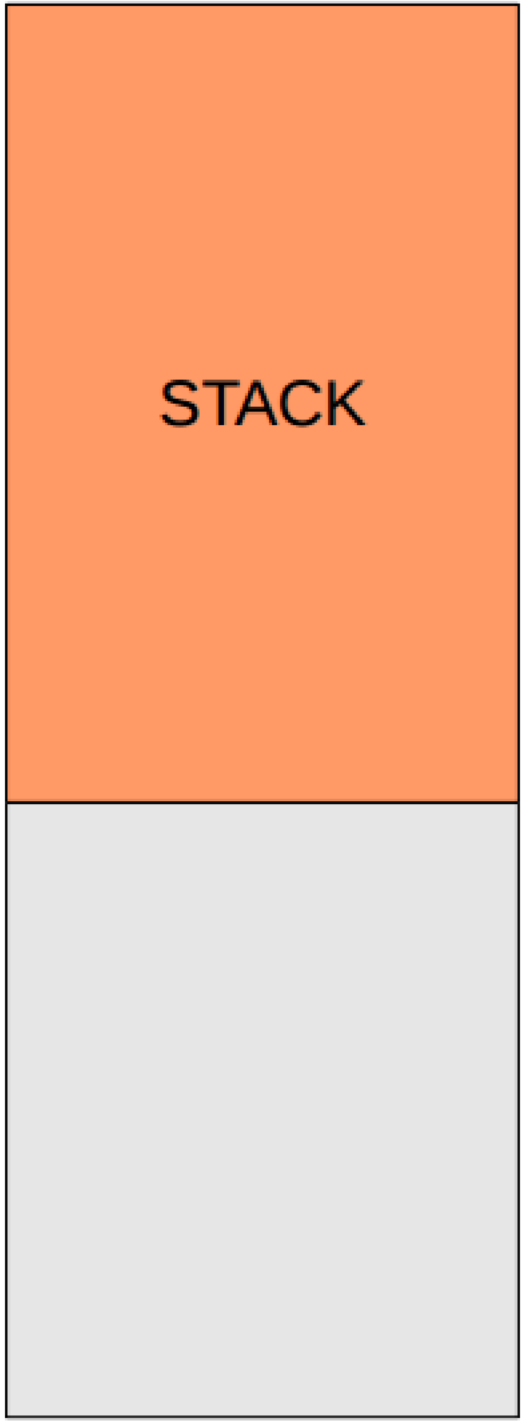
Consider the following stack.

What happens when I do:

    pushl %ebp

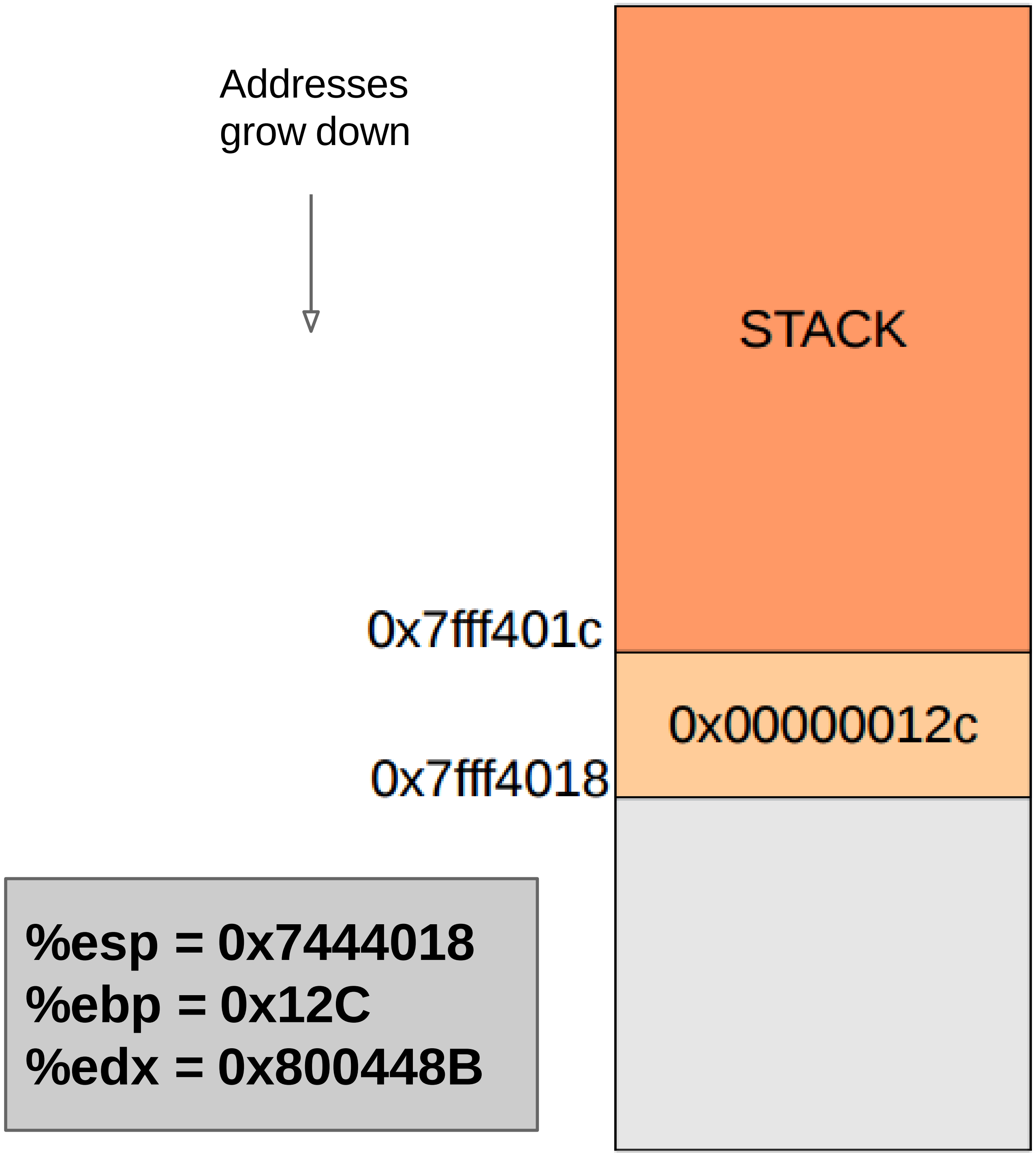
Addresses grow down

0x7fff401c



%esp = 0x744401C
%ebp = 0x12C
%edx = 0x800448B

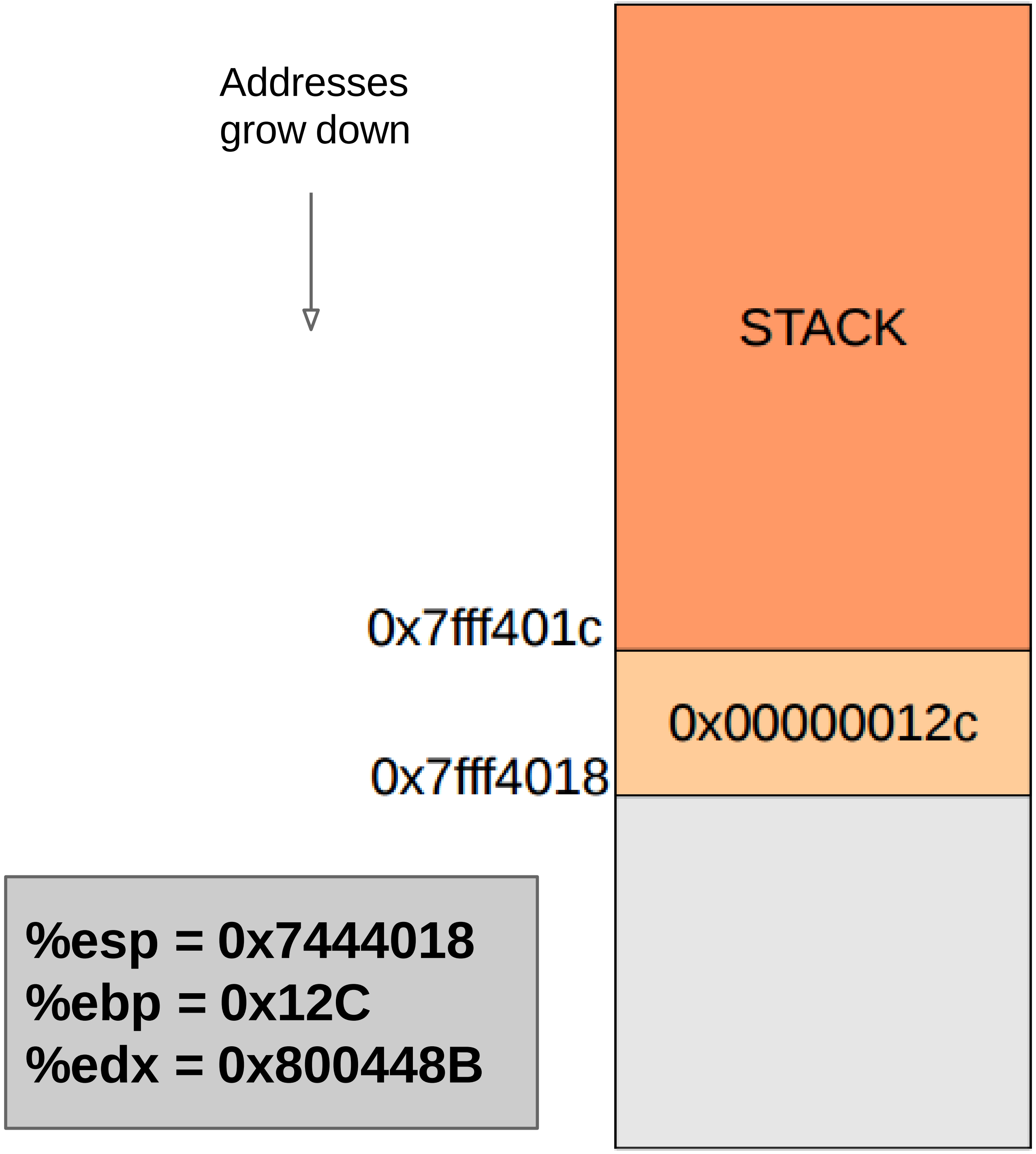
The Stack


Addresses
grow down
STACK
0x7fff401c
0x0000012c
0x7fff4018
%esp = 0x7444018
%ebp = 0x12C
%edx = 0x800448B

The Stack

What happens when I do:

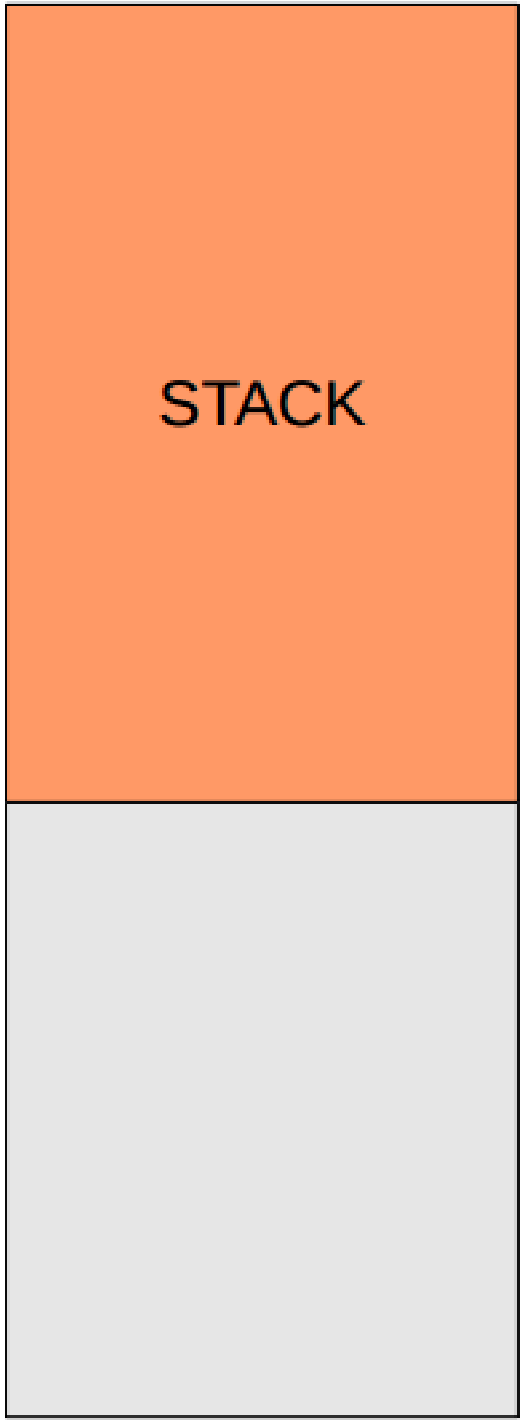
popl %edx



The Stack

Addresses
grow down

0x7fff401c



%esp = 0x744401C
%ebp = 0x12C
%edx = 0x12C

Exercise: Fun with arithmetic

(a) C code

```
int arith(int x,
          int y,
          int z)
{
    int t1 = x+y;
    int t2 = z*48;
    int t3 = t1 & 0xFFFF;
    int t4 = t2 * t3;
    return t4;
}
```

Figure 3.8 **C and assembly code for arithmetic routine body.** The stack set-up and completion portions have been omitted.

Convert this function to x86. Assume that: `x at %ebp+8, y at %ebp+12, z at %ebp+16.`
Recall: `addl src dst, imull src dst, andl src dst.`

Exercise: Fun with arithmetic

Section 3.5 Arithmetic and Logical Operations **181**

(a) C code

```c
int arith(int x,
          int y,
          int z)
{
    int t1 = x+y;
    int t2 = z*48;
    int t3 = t1 & 0xFFFF;
    int t4 = t2 * t3;
    return t4;
}
```

(b) Assembly code

```
x at %ebp+8, y at %ebp+12, z at %ebp+16
    movl    16(%ebp), %eax         z
    leal    (%eax,%eax,2), %eax    z*3
    sall    $4, %eax               t2 = z*48
    movl    12(%ebp), %edx         y
    addl    8(%ebp), %edx          t1 = x+y
    andl    $65535, %edx           t3 = t1&0xFFFF
    imull   %edx, %eax             Return t4 = t2*t3
```

Figure 3.8 **C and assembly code for arithmetic routine body.** The stack set-up and completion portions have been omitted.

Does this make sense? Note the usage of `leal` and `sall`, rather than simply using `imull`. Using `imull` isn't wrong - but it's good to be able to see why both approaches work!