

CS107, Lecture 16

Assembly: Arithmetic and Logic

Reading: B&O 3.5-3.6

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Based on slides created by Cynthia Lee, Chris Gregg, Jerry Cain, Lisa Yan and others.

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CS107 Topic 5

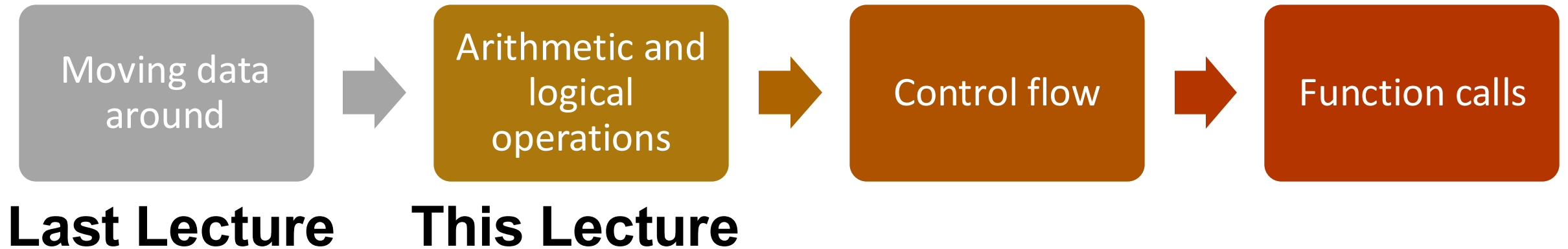
How does a computer interpret and execute C programs?

Why is answering this question important?

- Learning how our code is really translated and executed helps us write better code
- We can learn how to reverse engineer and exploit programs at the assembly level

assign5: find and exploit vulnerabilities in an ATM program, reverse engineer a program without seeing its code, and de-anonymize users given a data leak.

Learning Assembly



Reference Sheet: cs107.stanford.edu/resources/x86-64-reference.pdf
See more guides on Resources page of course website!

Helpful Assembly Resources

- **Course textbook** (reminder: see relevant readings for each lecture on the Calendar page, <http://cs107.stanford.edu/calendar.html>)
- **CS107 Assembly Reference Sheet:** <http://cs107.stanford.edu/resources/x86-64-reference.pdf>
- **CS107 Guide to x86-64:** <http://cs107.stanford.edu/guide/x86-64.html>

Learning Goals

- Learn how to perform arithmetic and logical operations in assembly
- Begin to learn how to read assembly and understand the C code that generated it

Lecture Plan

- **Recap: mov** so far
- Data and Register Sizes
- The **lea** Instruction

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Lecture Plan

- **Recap: mov so far**
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mov

The **mov** instruction copies bytes from one place to another; it is similar to the assignment operator (=) in C.

mov **src, dst**

The **src** and **dst** can each be one of:

- Immediate (constant value, like a number) (*only src*)
- Register
- Memory Location
(*at most one of src, dst*)

mov

The **mov** instruction copies bytes from one place to another.

mov src , dst

Options include:

“Copy this exact value somewhere”

Immediate, e.g. \$0x401

mov

The **mov** instruction copies bytes from one place to another.

mov *src* , *dst*

Options include:

“Copy this exact value somewhere”

Immediate, e.g. \$0x401

“Copy what’s in this register somewhere, or copy something into this register”

Register, e.g. %rax

Register, e.g. %rax

mov

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mov src , dst

Options include:

“Copy this exact value somewhere”

Immediate, e.g. \$0x401

“Copy what’s in this register somewhere, or copy something into this register”

Register, e.g. %rax

Register, e.g. %rax

Memory Location

Memory Location

“Copy what’s at this memory location somewhere, or copy something to this location in memory”

mov

The **mov** instruction copies bytes from one place to another.

mov *src* , *dst*

Options include:

“Copy this exact value somewhere”

Immediate, e.g. \$0x401

“Copy what’s in this register somewhere, or copy something into this register”

Register, e.g. %rax

Register, e.g. %rax

Memory Location

Memory Location

“Copy what’s at this memory location somewhere, or copy something to this location in memory”

Memory Location Syntax

Hardcoded address (e.g. 0x104) or..

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Hardcoded address (e.g. 0x104) or...

Immediate (register1, register2, scale factor)

e.g.

`0x4(%rax,%rdx,2)`

“Go to address **Immediate + register1 + (register2 * scale factor)**”

Key idea: any of the parts of this form can be omitted, in which case they are ignored.

Memory Location Syntax

Syntax	Go to this memory location:
0x104 (no \$)	0x104
(%rax)	What's in %rax
4(%rax)	What's in %rax, plus 4
(%rax, %rdx)	Sum of what's in %rax and %rdx
4(%rax, %rdx)	Sum of values in %rax and %rdx, plus 4
(, %rdx, 4)	What's in %rdx times 4
0x4(, %rdx, 4)	What's in %rdx times 4, plus 4
(%rax, %rdx, 2)	Sum of %rax and (what's in %rdx times 2)
0x4(%rax, %rdx, 2)	Sum of 0x4 and %rax and (what's in %rdx times 2) ⁵

Most General Operand Form

$\text{Imm}(r_b, r_i, s)$ is equivalent to
address $\text{Imm} + R[r_b] + R[r_i]*s$

Displacement:
pos/neg constant
(if missing, = 0)

Base: register (if
missing, = 0)

Index: register
(if missing, = 0)

Scale must be
1,2,4, or 8
(if missing, = 1)

Practice #3: Operand Forms

What are the results of the following move instructions (executed separately)? For this problem, assume the value $0x1$ is stored in register `%rcx`, the value $0x100$ is stored in register `%rax`, the value $0x3$ is stored in register `%rdx`, and value $0x11$ is stored at address $0x10C$.

1. `mov $0x42,0xfc(,%rcx,4)`

2. `mov (%rax,%rdx,4),%rbx`

For #2, respond with your thoughts on PollEv:
pollev.com/cs107



$\text{Imm}(r_b, r_i, s)$ is equivalent to
address $\text{Imm} + R[r_b] + R[r_i]*s$
Displacement Base Index Scale
(1,2,4,8)

For #2, what is in %rbx after this instruction?

0x10C

0%

0x100

0%

0x104

0%

0x11

0%

Goals of indirect addressing: C

Why are there so many forms of indirect addressing?

We see these indirect addressing paradigms in C as well!

From Assembly to C

What might be the equivalent C-like operation?

1. `mov $0x0,%rdx`
2. `mov %rdx,%rcx`
3. `mov $0x42,(%rdi)`
4. `mov (%rax,%rcx,8),%rax`



From Assembly to C

What might be the equivalent C-like operation?

1. `mov $0x0,%rdx` -> maybe `long x = 0`
2. `mov %rdx,%rcx` -> maybe `long x = y;`
3. `mov $0x42,(%rdi)` -> maybe `*ptr = 0x42;`
4. `mov (%rax,%rcx,8),%rax` -> maybe `long x = arr[i];`

Indirect addressing
is like pointer
arithmetic/deref!

Scale Factor and Array Indexing

The scale factor is useful because in assembly, pointer arithmetic is done in terms of bytes, *not* number of places like in C. For example:

```
long arr[5];
```

...

```
long num = arr[3];
```

This last line of code in assembly could be:

```
mov (%rdi, %rcx, 8),%rax
```

<val of num>

%rax

3

%rcx

<val of arr>

%rdi

Lecture Plan

- **Recap: mov** so far
- **Data and Register Sizes**
- The **lea** Instruction

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Data Sizes

Data sizes in assembly have slightly different terminology to get used to:

- A **byte** is 1 byte.
- A **word** is 2 bytes.
- A **double word** is 4 bytes.
- A **quad word** is 8 bytes.

Assembly instructions can have suffixes to refer to these sizes:

- b means **byte**
- w means **word**
- l means **double word**
- q means **quad word**

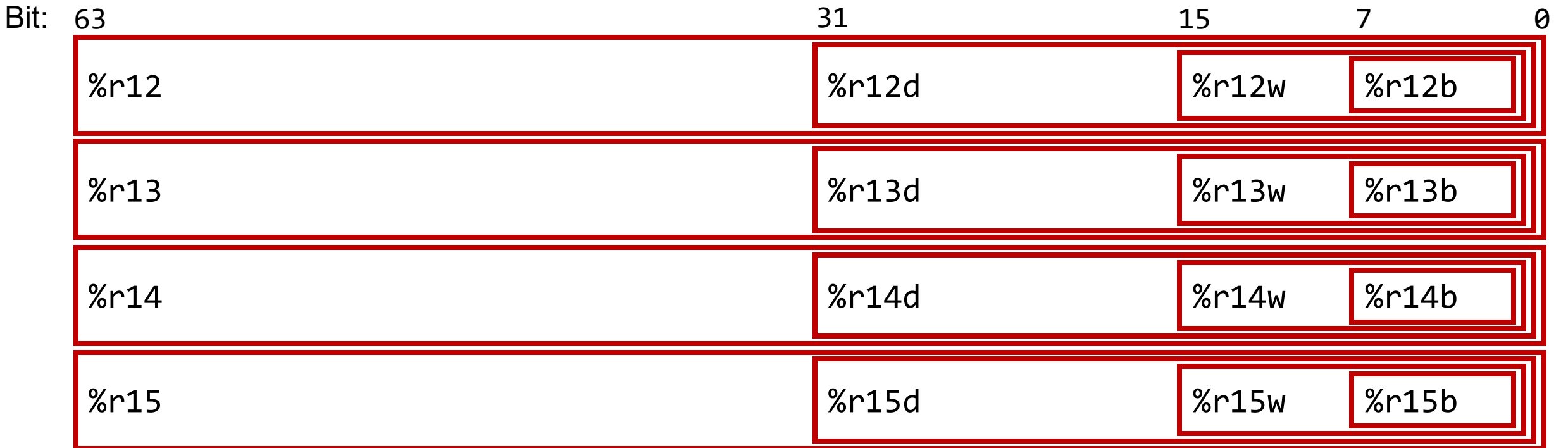
Register Sizes

Bit:	63	31	15	7	0
%rax	%eax		%ax	%al	
%rbx	%ebx		%bx	%bl	
%rcx	%ecx		%cx	%cl	
%rdx	%edx		%dx	%dl	
%rsi	%esi		%si	%sil	
%rdi	%edi		%di	%dil	

Register Sizes

Bit:	63	31	15	7	0
%rbp		%ebp	%bp	%bpl	
%rsp		%esp	%sp	%spl	
%r8		%r8d	%r8w	%r8b	
%r9		%r9d	%r9w	%r9b	
%r10		%r10d	%r10w	%r10b	
%r11		%r11d	%r11w	%r11b	

Register Sizes



Register Responsibilities

Some registers take on special responsibilities during program execution.

- **%rax** stores the return value
- **%rdi** stores the first parameter to a function
- **%rsi** stores the second parameter to a function
- **%rdx** stores the third parameter to a function
- **%rip** stores the address of the next instruction to execute
- **%rsp** stores the address of the current top of the stack

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mov Variants

- **mov** can take an optional suffix (b,w,l,q) that specifies the size of data to move:
movb, movw, movl, movq
- **mov** only updates the specific register bytes or memory locations indicated.
 - **Exception: movl** writing to a register will also set high order 4 bytes to 0.

Practice: mov And Data Sizes

Sometimes, you might see mov suffixes that specify the amount of data being moved. Other times, they are omitted if we can deduce the size from the arguments.

```
movl %eax, (%rsp)
```

```
movw (%rax), %dx
```

```
movb (%rsp, %rdx, 4), %dl
```

```
mov $0x0, %eax
```

movz and movs

- There are two mov instructions that can be used to copy a smaller source to a larger destination: **movz** and **movs**.
- **movz** fills the remaining bytes with zeros
- **movs** fills the remaining bytes by sign-extending the most significant bit in the source.
- The source must be from memory or a register, and the destination is a register.

movz and movs

MOVZ S, R

$R \leftarrow \text{ZeroExtend}(S)$

Instruction	Description
movzwb	Move zero-extended byte to word
movzbl	Move zero-extended byte to double word
movzwl	Move zero-extended word to double word
movzbq	Move zero-extended byte to quad word
movzwq	Move zero-extended word to quad word

movz and movs

MOVS S, R

$R \leftarrow \text{SignExtend}(S)$

Instruction	Description
movsbw	Move sign-extended byte to word
movsbl	Move sign-extended byte to double word
movswl	Move sign-extended word to double word
movsbq	Move sign-extended byte to quad word
movswq	Move sign-extended word to quad word
movslq	Move sign-extended double word to quad word
cltq	Sign-extend %eax to %rax $\%rax \leftarrow \text{SignExtend}(\%eax)$

Register Sizes

- The operand forms with parentheses (e.g. **mov (%rax)**) require that registers in parentheses be the 64-bit registers.
- For that reason, you may see smaller registers extended with e.g. **movs** into the larger registers before these kinds of instructions.

Our First Assembly

```
int sum_array(int arr[], int nelems) {  
    int sum = 0;  
    for (int i = 0; i < nelems; i++) {  
        sum += arr[i];  
    }  
    return sum;  
}
```

000000000401136 <sum_array>:

401136:	b8 00 00 00 00	mov	\$0x0,%eax
40113b:	ba 00 00 00 00	mov	\$0x0,%edx
401140:	39 f0	cmp	%esi,%eax
401142:	7d 0b	jge	40114f <sum_array+0x19>
401144:	48 63 c8	movslq	%eax,%rcx
401147:	03 14 8f	add	(%rdi,%rcx,4),%edx
40114a:	83 c0 01	add	\$0x1,%eax
40114d:	eb f1	jmp	401140 <sum_array+0xa>
40114f:	89 d0	mov	%edx,%eax
401151:	c3	retq	

Lecture Plan

- **Recap: mov** so far
- Data and Register Sizes
- **The lea Instruction**

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lea

The **lea** instruction copies an “effective address” from one place to another.

lea **src, dst**

Unlike **mov**, which copies data at the address **src** to the destination, **lea** copies the value of **src** *itself* to the destination. Destination must be a register.

The syntax for the destinations is the same as **mov**. The difference is how it handles the **src**.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
6(%rax), %rdx	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
6(%rax), %rdx	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.
(%rax, %rcx), %rdx	Go to the address (what's in %rax + what's in %rcx) and copy data there into %rdx	Copy (what's in %rax + what's in %rcx) into %rdx.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
6(%rax), %rdx	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.
(%rax, %rcx), %rdx	Go to the address (what's in %rax + what's in %rcx) and copy data there into %rdx	Copy (what's in %rax + what's in %rcx) into %rdx.
(%rax, %rcx, 4), %rdx	Go to the address (%rax + 4 * %rcx) and copy data there into %rdx.	Copy (%rax + 4 * %rcx) into %rdx.

lea vs. mov

Operands	mov Interpretation	lea Interpretation
<code>6(%rax), %rdx</code>	Go to the address (6 + what's in %rax), and copy data there into %rdx	Copy 6 + what's in %rax into %rdx.
<code>(%rax, %rcx), %rdx</code>	Go to the address (what's in %rax + what's in %rcx) and copy data there into %rdx	Copy (what's in %rax + what's in %rcx) into %rdx.
<code>(%rax, %rcx, 4), %rdx</code>	Go to the address ($\%rax + 4 * \%rcx$) and copy data there into %rdx.	Copy ($\%rax + 4 * \%rcx$) into %rdx.
<code>7(%rax, %rax, 8), %rdx</code>	Go to the address ($7 + \%rax + 8 * \%rax$) and copy data there into %rdx.	Copy ($7 + \%rax + 8 * \%rax$) into %rdx.

Unlike **mov**, which copies data at the address `src` to the destination, **lea** copies the value of `src` *itself* to the destination.

Reverse Engineering Practice

```
void calculate(int x, int y, int *ptr) {  
    _____?_____;  
}
```

```
calculate:  
    leal (%rdi,%rsi,2), %eax  
    movl %eax, (%rdx)  
    ret
```

Note: assume x is in %rdi, y is in %rsi and ptr is in %rdx.

Reverse Engineering Practice

```
void calculate(int x, int y, int *ptr) {  
    *ptr = x + 2 * y;  
}
```

```
calculate:  
    leal (%rdi,%rsi,2), %eax  
    movl %eax, (%rdx)  
    ret
```

A Note About Operand Forms

- Many instructions we will see share the same address operand forms that **mov** uses.
 - Eg. `7(%rax, %rcx, 2)`.
- These forms work the same way for other instructions, with the exception of **lea**:
 - It interprets this form as just the calculation, *not the dereferencing*
 - `lea 8(%rax,%rdx),%rcx` -> Calculate $8 + \%rax + \%rdx$, put it in `%rcx`

Summary: parentheses means “dereference”, except for with **lea**.

Unary Instructions

The following instructions operate on a single operand (register or memory):

Instruction	Effect	Description
<code>inc D</code>	$D \leftarrow D + 1$	Increment
<code>dec D</code>	$D \leftarrow D - 1$	Decrement
<code>neg D</code>	$D \leftarrow -D$	Negate
<code>not D</code>	$D \leftarrow \sim D$	Complement

Examples:

```
incq 16(%rax)
```

```
dec %rdx
```

```
not %rcx
```

Binary Instructions

The following instructions operate on two operands (both can be register or memory, source can also be immediate). Both cannot be memory locations. Read it as, e.g. “Subtract S from D”:

Instruction	Effect	Description
add S, D	$D \leftarrow D + S$	Add
sub S, D	$D \leftarrow D - S$	Subtract
imul S, D	$D \leftarrow D * S$	Multiply
xor S, D	$D \leftarrow D \wedge S$	Exclusive-or
or S, D	$D \leftarrow D S$	Or
and S, D	$D \leftarrow D \& S$	And

Examples:

```
addq %rcx, (%rax)
```

```
xorq $16, (%rax, %rdx, 8)
```

```
subq %rdx, 8(%rax)
```

Recap

- **Recap: mov** so far
- Data and Register Sizes
- The **lea** Instruction

Next Time: more arithmetic operations, and reverse engineering practice

Lecture 16 takeaway: **mov** has a variety of forms to specify an address – they are all variations of one overall form. There are also different register sizes that may be used in assembly instructions. **lea** is an instruction used for arithmetic that shares the same operand form as **mov**, but **lea** interprets them differently.

Extra Practice

1. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. **results in** this register layout

```
long arr[5];
```

```
...
```

```
long num = _____???
```

```
mov (%rdi, %rcx, 8),%rax
```

<val of num>

%rax

3

%rcx

<val of arr>

%rdi



1. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. **results in** this register layout

```
long arr[5];  
...  
long num = _____???
```

```
long num = arr[3];  
long num = *(arr + 3);  
long num = *(arr + y);
```

(assume long y = 3;
declared earlier)

```
mov (%rdi, %rcx, 8),%rax
```

<val of num>

%rax

3

%rcx

<val of arr>

%rdi

2. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. has this register layout

```
char str[5];
```

```
...
```

```
___???___ = 'c';
```

```
mov $0x63, (%rcx,%rdx,1)
```

<val of str>

%rcx

2

%rdx



2. Extra Practice

Fill in the blank to complete the C code that

1. generates this assembly
2. has this register layout

```
char str[5];
```

...

```
____? ? ? ____ = 'c';
```

```
str[2] = 'c';  
*(str + 2) = 'c';
```

```
mov $0x63, (%rcx,%rdx,1)
```

<val of str>

%rcx

2

%rdx