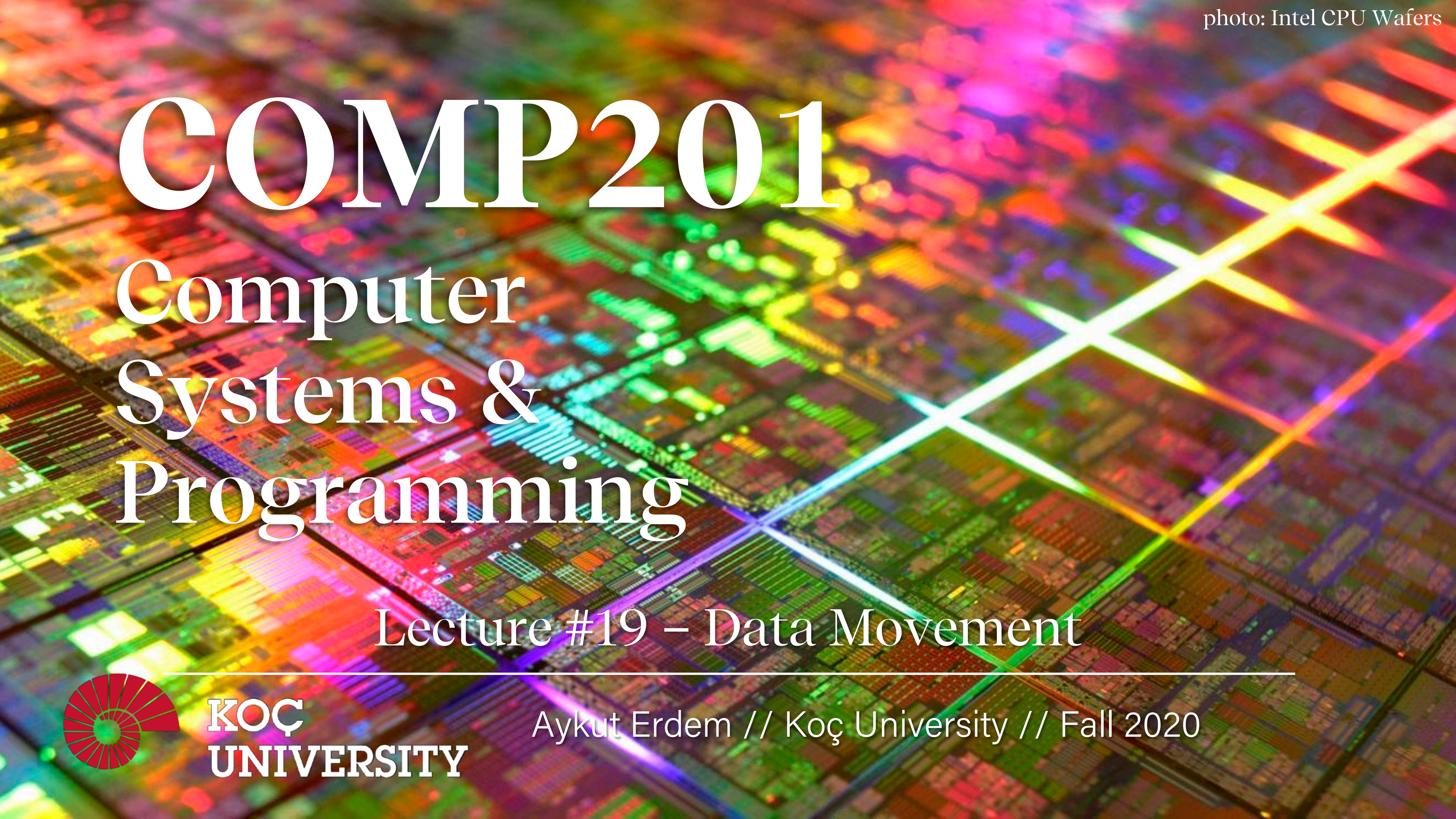


photo: Intel CPU Wafers

COMP201

Computer Systems & Programming

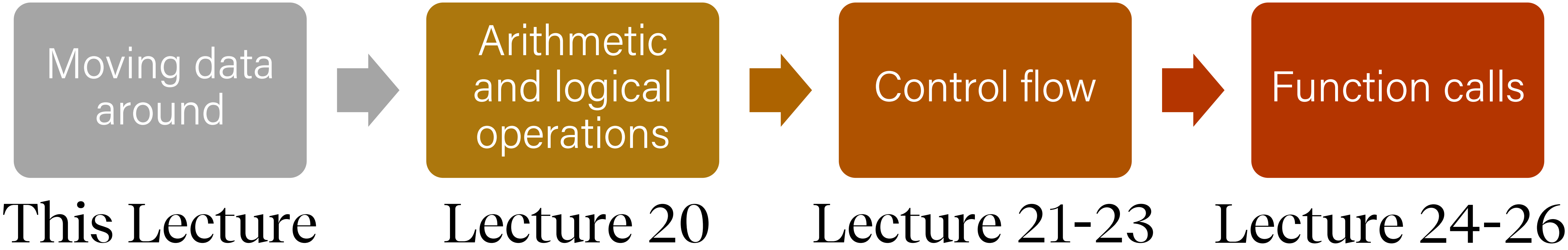
Lecture #19 – Data Movement

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Fall 2020

COMP201 Topic 6: How does a computer interpret and execute C programs?

Learning Assembly



Moving data around

This Lecture

Arithmetic and logical operations

Lecture 20

Control flow

Lecture 21-23

Function calls

Lecture 24-26

Lecture Plan

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

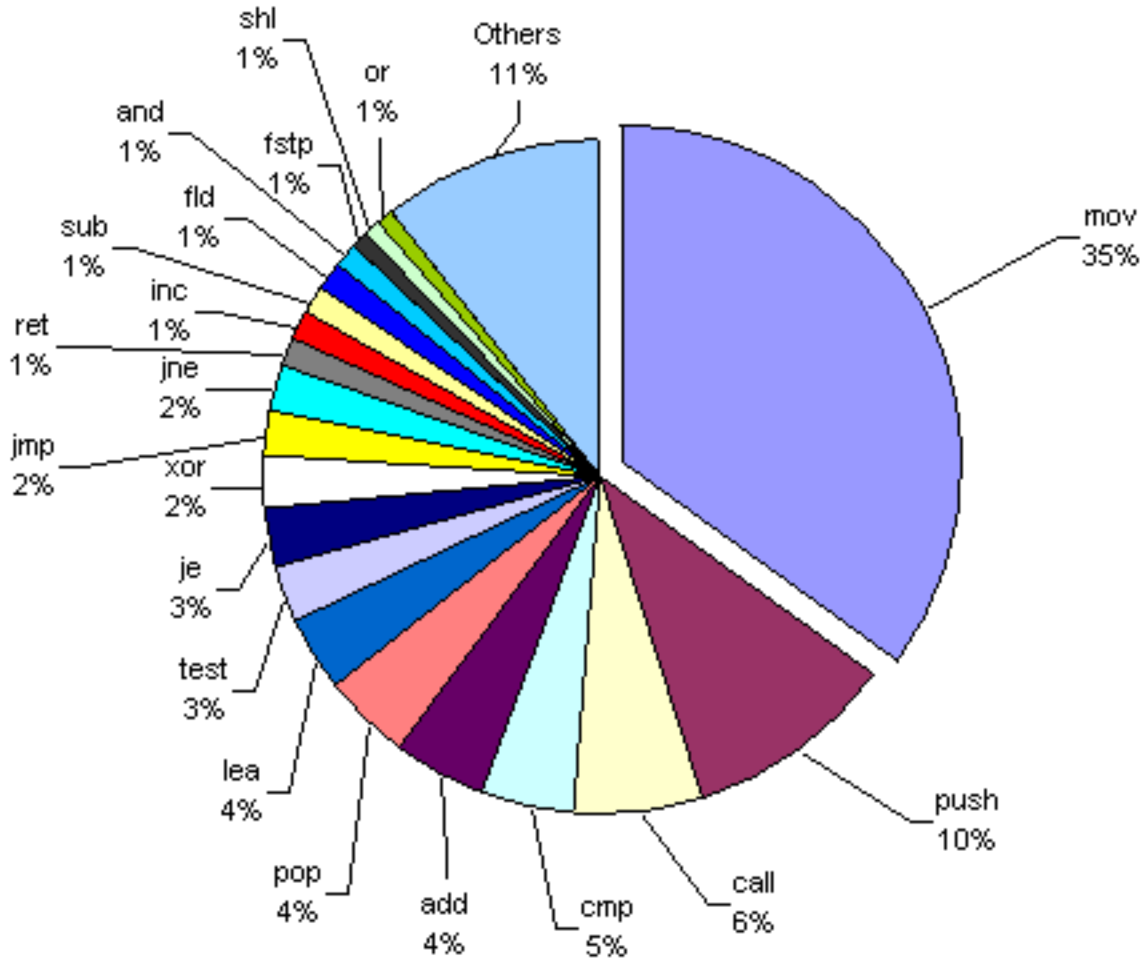
Disclaimer: Slides for this lecture were borrowed from

—Nick Troccoli's Stanford CS107 class

Lecture Plan

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

Top 20 instructions of x86 architecture



Source: https://www.strchr.com/x86_machine_code_statistics

`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***) **`$0x104`**
- Register **`%rbx`**
- Memory Location (*at most one of **src, dst***) Direct address **`0x6005c0`**

Operand Forms: Immediate

```
mov      $0x104,_____
```

Copy the value 0x104 into some destination.

Operand Forms: Registers

Copy the value in register %rbx into some destination.

```
mov        %rbx,____
```

```
mov        ____,%rbx
```

Copy the value from some source into register %rbx.

Operand Forms: Absolute Addresses

Copy the value at address 0x104 into some destination.

```
mov     0x104,_____
```

```
mov     _____,0x104
```

Copy the value from some source into the memory at address 0x104.

Operand Forms: Indirect

Copy the value at the address stored in register %rbx into some destination.

```
mov        (%rbx),_____
```

```
mov        _____,(%rbx)
```

Copy the value from some source into the memory at the address stored in register %rbx.

Operand Forms: Base + Displacement

*Copy the value at the address (**0x10 plus** what is stored in register %rax) into some destination.*

```
mov     0x10(%rax),__________

mov     __________,0x10(%rax)
```

*Copy the value from some source into the memory at the address (**0x10 plus** what is stored in register %rax).*

Operand Forms: Indexed

Copy the value at the address which is (the sum of the values in registers %rax and %rdx) into some destination.

```
mov     (%rax,%rdx),__________

mov     __________,(%rax,%rdx)
```

Copy the value from some source into the memory at the address which is (the sum of the values in registers %rax and %rdx).

Operand Forms: Indexed

Copy the value at the address which is (the sum of ***0x10 plus*** *the values in registers %rax and %rdx) into some destination.*

```
mov     0x10(%rax,%rdx),______
```

```
mov     _______,0x10(%rax,%rdx)
```

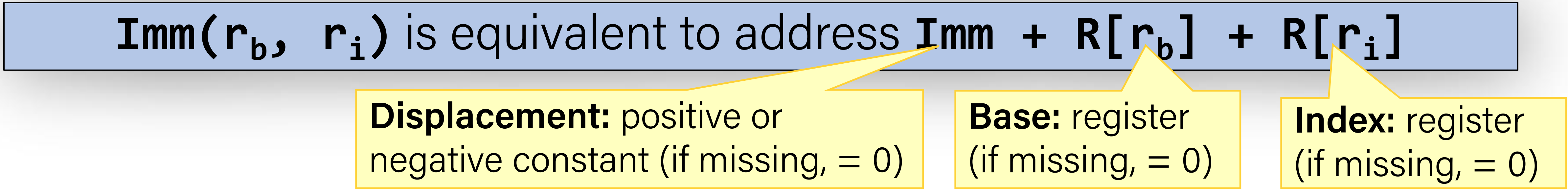
Copy the value from some source into the memory at the address which is (the sum of ***0x10 plus*** *the values in registers %rax and %rdx).*

Practice #1: Operand Forms

What are the results of the following move instructions (executed separately)? For this problem, assume

the value *0x11* is stored at address *0x10C*,
the value *0xAB* is stored at address *0x104*,
0x100 is stored in register %rax and *0x3* is stored in %rdx.

1. `mov $0x42,(%rax)` Move 0x42 to memory address 0x100
2. `mov 4(%rax),%rcx` Move 0xAB into %rcx
3. `mov 9(%rax,%rdx),%rcx` Move 0x11 into %rcx



$\texttt{Imm}(\texttt{r}_\texttt{b}, \texttt{r}_\texttt{i})$ is equivalent to address $\texttt{Imm} + \texttt{R}[\texttt{r}_\texttt{b}] + \texttt{R}[\texttt{r}_\texttt{i}]$

Displacement: positive or negative constant (if missing, = 0)

Base: register (if missing, = 0)

Index: register (if missing, = 0)

Operand Forms: Scaled Indexed

*Copy the value at the address which is (**4 times** the value in register %rdx) into some destination.*

```
mov     (,%rdx,4),________
```

```
mov     ________,(,%rdx,4)
```

The *scaling factor* (e.g. 4 here) must be hardcoded to be either 1, 2, 4 or 8.

*Copy the value from some source into the memory at the address which is (**4 times** the value in register %rdx).*

Operand Forms: Scaled Indexed

Copy the value at the address which is (4 times the value in register %rdx, ***plus 0x4****), into some destination.*

```
mov     0x4(,%rdx,4),______
```

```
mov     _______,0x4(,%rdx,4)
```

Copy the value from some source into the memory at the address which is (4 times the value in register %rdx, ***plus 0x4).***

Operand Forms: Scaled Indexed

*Copy the value at the address which is (**__the value in register %rax__** plus 2 times the value in register %rdx) into some destination.*

```
mov    (%rax,%rdx,2),__________
```

```
mov    __________,(%rax,%rdx,2)
```

*Copy the value from some source into the memory at the address which is (**__the value in register %rax__** plus 2 times the value in register %rdx).*

Operand Forms: Scaled Indexed

*Copy the value at the address which is (**0x4 plus** the value in register %rax plus 2 times the value in register %rdx) into some destination.*

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

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

*Copy the value from some source into the memory at the address which is (**0x4 plus** the value in register %rax plus 2 times the value in register %rdx).*

Most General Operand Form

$\mathtt{Imm(r_b,r_i,s)}$

is equivalent to…

$\mathtt{Imm + R[r_b] + R[r_i]*s}$

Most General Operand Form

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

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)

Memory Location Syntax

Syntax	Meaning
`0x104`	Address `0x104` (no `$`)
`(%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
`(, %rcx, 4)`	What’s in `%rcx`, times 4 (multiplier can be 1, 2, 4, 8)
`(%rax, %rcx, 2)`	What’s in `%rax`, plus 2 times what’s in `%rcx`
`8(%rax, %rcx, 2)`	What’s in `%rax`, plus 2 times what’s in `%rcx`, plus 8

Operand Forms

Type	Form	Operand Value	Name
Immediate	$\$Imm$	Imm	Immediate
Register	r_a	$R[r_a]$	Register
Memory	Imm	$M[Imm]$	Absolute
Memory	(r_a)	$M[R[r_a]]$	Indirect
Memory	$Imm(r_b)$	$M[Imm + R[r_b]]$	Base + displacement
Memory	(r_b, r_i)	$M[R[r_b] + R[r_i]]$	Indexed
Memory	$Imm(r_b, r_i)$	$M[Imm + R[r_b] + R[r_i]]$	Indexed
Memory	$(, r_i, s)$	$M[R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(, r_i, s)$	$M[Imm + R[r_i] \cdot s]$	Scaled indexed
Memory	(r_b, r_i, s)	$M[R[r_b] + R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(r_b, r_i, s)$	$M[Imm + R[r_b] + R[r_i] \cdot s]$	Scaled indexed

Figure 3.3 from the book: “Operand forms. Operands can denote immediate (constant) values, register values, or values from memory. The scaling factor s must be either. 1, 2, 4, or 8.”

Practice #2: 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
the value *0x11* is stored at address *0x10C*.

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

Move 0x42 to memory address 0x100

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

Move 0x11 into %rbx

$\mathtt{Imm}(\mathtt{r}_\mathtt{b}, \mathtt{r}_\mathtt{i}, \mathtt{s})$ *is equivalent to address* **$\mathtt{Imm} + \mathtt{R}[\mathtt{r}_\mathtt{b}] + \mathtt{R}[\mathtt{r}_\mathtt{i}]*\mathtt{s}$**

Displacement Base Index Scale

(1,2,4,8)

Goals of indirect addressing: C

Why are there so many forms of indirect addressing?

We see these indirect addressing paradigms in C as well!

Extra Practice

Extra Practice

slido Event code: 73165

Fill in the blank to complete the code that generated the assembly below.

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

```
// %rdi stores arr, %rcx stores 3, and %rax stores num
mov (%rdi, %rcx, 8),%rax
```

Extra Practice

slido Event code: 73165

Fill in the blank to complete the code that generated the assembly below.

```
long arr[5];
...
long num = arr[3];
```

```
// %rdi stores arr, %rcx stores 3, and %rax stores num
mov (%rdi, %rcx, 8),%rax
```

Extra Practice

slido Event code: 73165

Fill in the blank to complete the code that generated the assembly below.

```
int x = ...
int *ptr = malloc(…);
___???___ = x;
```

```
// %ecx stores x, %rax stores ptr
mov %ecx,(%rax)
```

Extra Practice

slido Event code: 73165

Fill in the blank to complete the code that generated the assembly below.

```
int x = ...
int *ptr = malloc(…);
*ptr = x;
```

```
// %ecx stores x, %rax stores ptr
mov %ecx,(%rax)
```

Extra Practice

slido Event code: 73165

Fill in the blank to complete the code that generated the assembly below.

```
char str[5];
...
___???___ = 'c';
```

```
// %rcx stores str, %rdx stores 2
mov $0x63,(%rcx,%rdx,1)
```

Extra Practice

slido Event code: 73165

Fill in the blank to complete the code that generated the assembly below.

```
char str[5];
...
str[2] = 'c';
```

```
// %rcx stores str, %rdx stores 2
mov $0x63,(%rcx,%rdx,1)
```

Lecture Plan

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

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**

Data Sizes

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

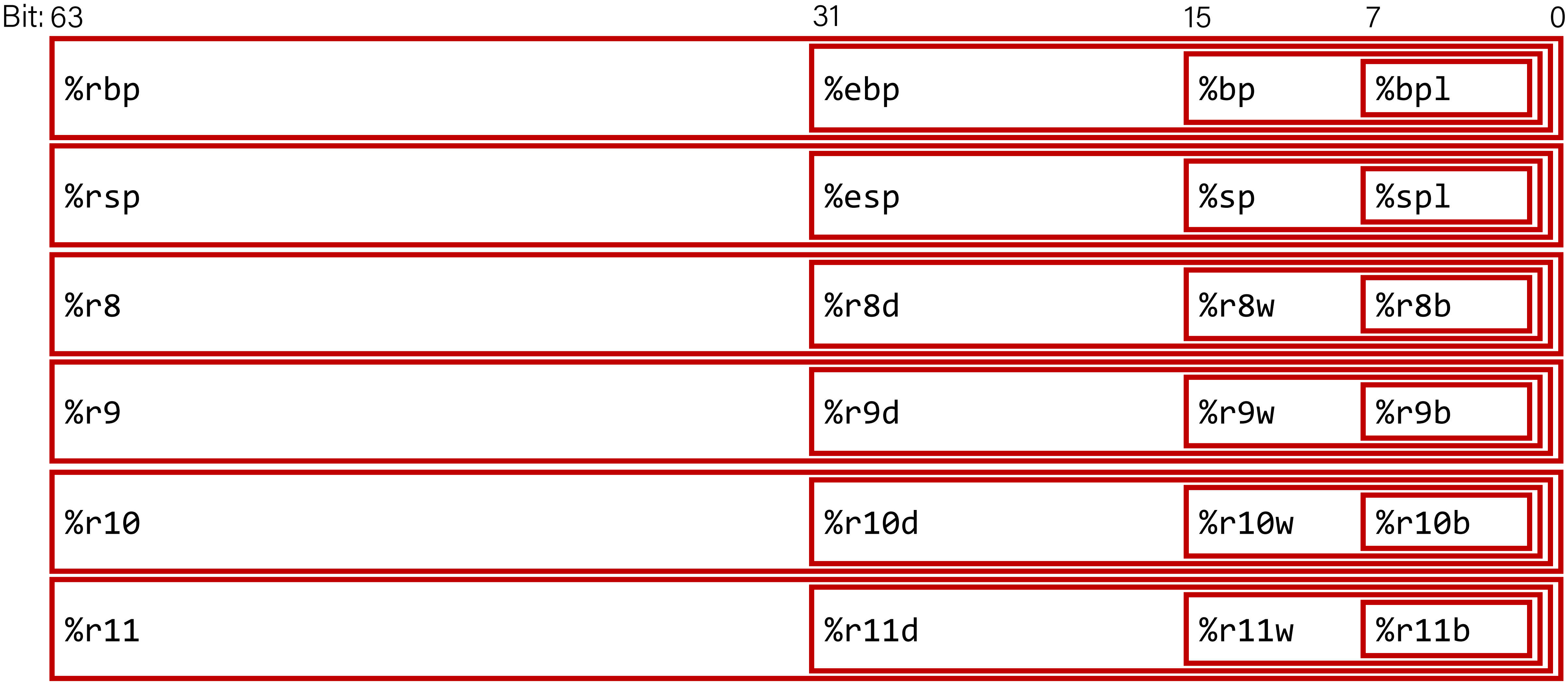
- A **byte** is 1 byte.
- A **word** is 2 bytes.
- A **double word** is 4 bytes.
- A **quad word** is 8 bytes.

C Type	Suffix	Byte	Intel Data Type
`char`	`b`	1	Byte
`short`	`w`	2	Word
`int`	`l`	4	Double word
`long`	`q`	8	Quad word
`char *`	`q`	8	Quad word
`float`	`s`	4	Single precision
`double`	`l`	8	Double precision

Register Sizes

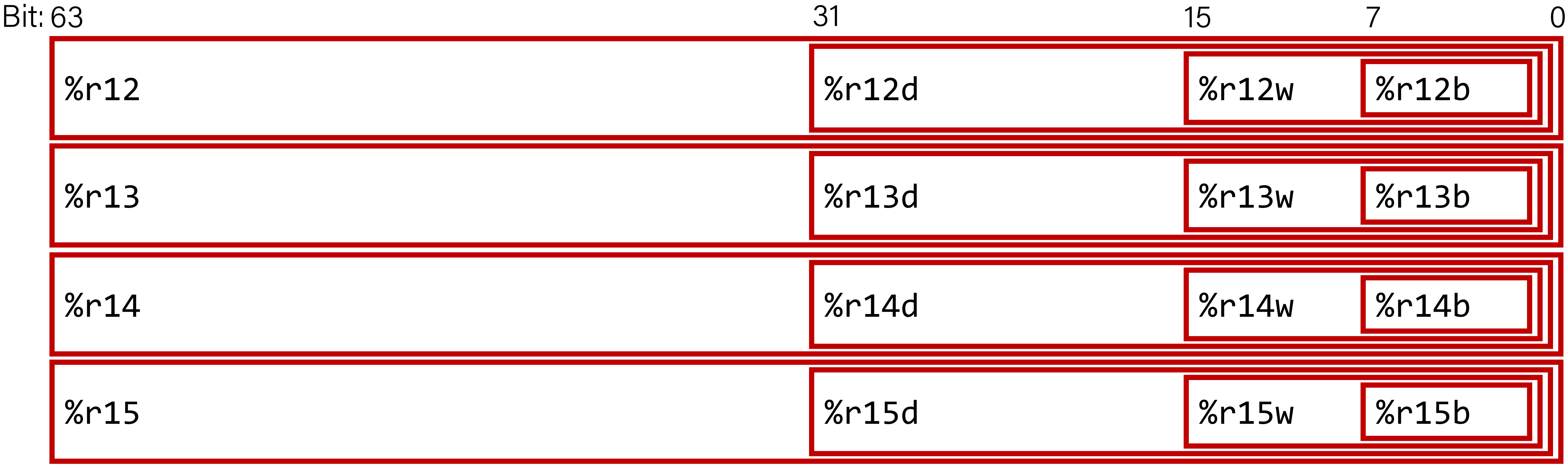
Bit: 63	31	15	7	0
%rax	%eax	%ax	%al	
%rbx	%ebx	%bx	%bl	
%rcx	%ecx	%cx	%cl	
%rdx	%edx	%dx	%dl	
%rsi	%esi	%si	%sil	
%rdi	%edi	%di	%dil	

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



Bit: 63 31 15 7 0

%r12 %r12d %r12w %r12b

%r13 %r13d %r13w %r13b

%r14 %r14d %r14w %r14b

%r15 %r15d %r15w %r15b

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

See **Stanford CS107 x86-64 Reference Sheet** on Resources page of the course website!
https://aykuterdem.github.io/classes/comp201/index.html#div_resources

`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 #3: `mov` And Data Sizes

For each of the following `mov` instructions, determine the appropriate suffix based on the operands (e.g. `movb`, `movw`, `movl` or `movq`).

```
1. mov__ %eax, (%rsp)              movl %eax, (%rsp)
2. mov__ (%rax), %dx               movw (%rax), %dx
3. mov__ $0xff, %bl                movb $0xff, %bl
4. mov__ (%rsp,%rdx,4),%dl         movb (%rsp,%rdx,4),%dl
5. mov__ (%rdx), %rax              movq (%rdx), %rax
6. mov__ %dx, (%rax)               movw %dx, (%rax)
```

mov

- The **movabsq** instruction is used to write a 64-bit Immediate (constant) value.
- The regular **movq** instruction can only take 32-bit immediates.
- 64-bit immediate as source, only register as destination.

```
movabsq $0x0011223344556677, %rax
```

Practice #4: `mov` And Data Sizes

For each of the following `mov` instructions, determine how data movement instructions modify the upper bytes of a destination register.

```
1. movabs $0x0011223344556677, %rax  %rax = 0011223344556677
2. movb $-1, %al                     %rax = 00112233445566FF
3. movw $-1, %ax                     %rax = 001122334455FFFF
4. movl $-1, %eax                    %rax = 00000000FFFFFFFF
5. movq $-1, %rax                    %rax = FFFFFFFFFFFFFFFF
```

`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 ← ZeroExtend(S)
```

Instruction	Description
`movzbw`	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 ← 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 <- SignExtend(%eax)`

Lecture Plan

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

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.

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
`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`.
`7(%rax, %rax, 8), %rdx`	Go to the address (7 + `%rax` + 8 * `%rax`) and copy data there into `%rdx`.	Copy (7 + `%rax` + 8 * `%rax`) into `%rdx`.

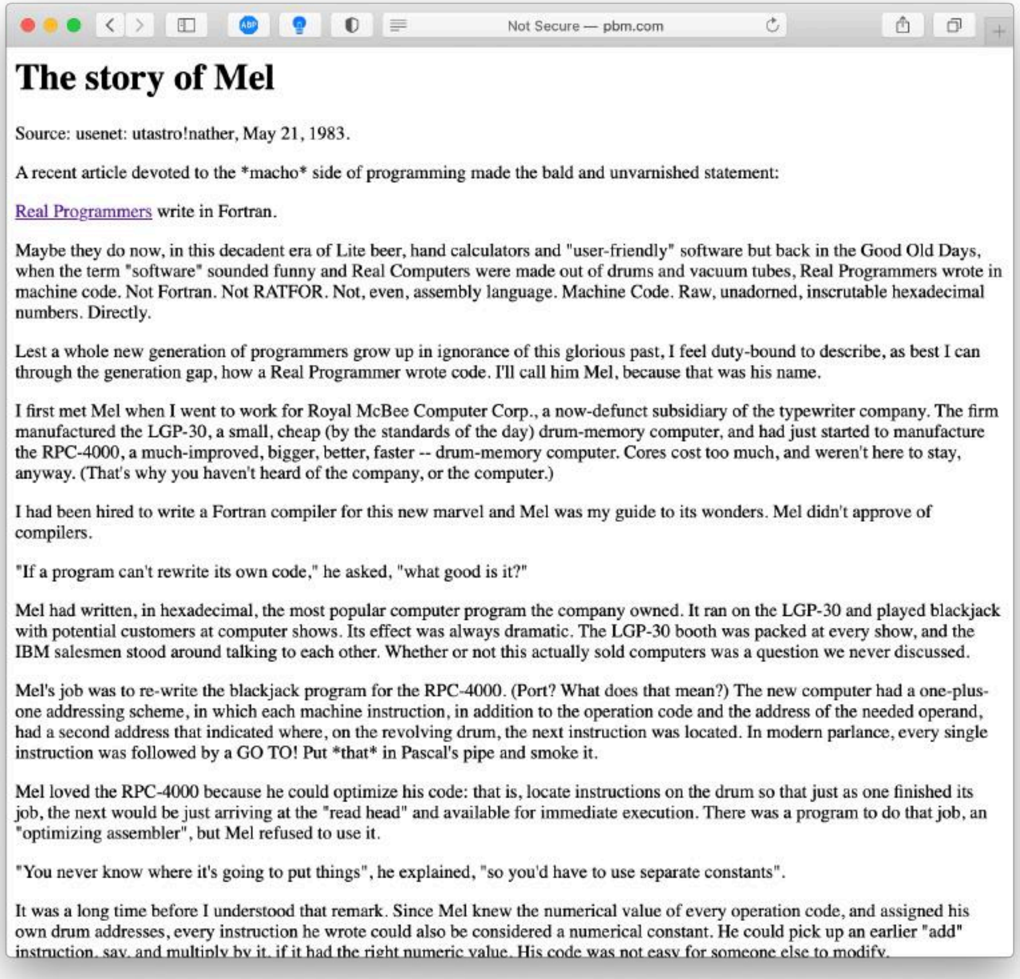
Unlike **`mov`**, which copies data <u>at</u> the address src to the destination, **`lea`** copies the value of src itself to the destination.

Recap

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

Next Time: Logical and Arithmetic Operations

Additional Reading



The story of Mel

Source: usenet: utastro!nather, May 21, 1983.

A recent article devoted to the *macho* side of programming made the bald and unvarnished statement:

Real Programmers write in Fortran.

Maybe they do now, in this decadent era of Lite beer, hand calculators and "user-friendly" software but back in the Good Old Days, when the term "software" sounded funny and Real Computers were made out of drums and vacuum tubes, Real Programmers wrote in machine code. Not Fortran. Not RATFOR. Not, even, assembly language. Machine Code. Raw, unadorned, inscrutable hexadecimal numbers. Directly.

Lest a whole new generation of programmers grow up in ignorance of this glorious past, I feel duty-bound to describe, as best I can through the generation gap, how a Real Programmer wrote code. I'll call him Mel, because that was his name.

I first met Mel when I went to work for Royal McBee Computer Corp., a now-defunct subsidiary of the typewriter company. The firm manufactured the LGP-30, a small, cheap (by the standards of the day) drum-memory computer, and had just started to manufacture the RPC-4000, a much-improved, bigger, better, faster -- drum-memory computer. Cores cost too much, and weren't here to stay, anyway. (That's why you haven't heard of the company, or the computer.)

I had been hired to write a Fortran compiler for this new marvel and Mel was my guide to its wonders. Mel didn't approve of compilers.

"If a program can't rewrite its own code," he asked, "what good is it?"

Mel had written, in hexadecimal, the most popular computer program the company owned. It ran on the LGP-30 and played blackjack with potential customers at computer shows. Its effect was always dramatic. The LGP-30 booth was packed at every show, and the IBM salesmen stood around talking to each other. Whether or not this actually sold computers was a question we never discussed.

Mel's job was to re-write the blackjack program for the RPC-4000. (Port? What does that mean?) The new computer had a one-plus-one addressing scheme, in which each machine instruction, in addition to the operation code and the address of the needed operand, had a second address that indicated where, on the revolving drum, the next instruction was located. In modern parlance, every single instruction was followed by a GO TO! Put *that* in Pascal's pipe and smoke it.

Mel loved the RPC-4000 because he could optimize his code: that is, locate instructions on the drum so that just as one finished its job, the next would be just arriving at the "read head" and available for immediate execution. There was a program to do that job, an "optimizing assembler", but Mel refused to use it.

"You never know where it's going to put things", he explained, "so you'd have to use separate constants".

It was a long time before I understood that remark. Since Mel knew the numerical value of every operation code, and assigned his own drum addresses, every instruction he wrote could also be considered a numerical constant. He could pick up an earlier "add" instruction, say, and multiply by it, if it had the right numeric value. His code was not easy for someone else to modify.

http://www.pbm.com/~lindahl/mel.html

LIBRASCOPE'S MURAL ROOM became a study hall for neophyte LPG-30 programmers the week of July 16. Students participating in this first training school for LPG-30 customers included (seated l. to r.) Bill Hopper, Mary Cornell and Chuck Rue, Convair-Pomona; John Corkhill, Convair-San Diego; R. J. Bibbins, Link Aviation; K. A. Hurst, D. D. Parkhurst, C. S. Kikushima and Ides J. Romero, Convair-San Diego; George Kendrick, Convair-Pomona; Chuck Ray, Caltech; and William Clayton, National Security Agency. Standing (l. to r.) are Fred Flannell, class instructor and assistant sales manager of Royal-McBee; and Royal-McBee Applications Engineers Bud Hazlett, Jack Behr and Mel Kaye. (Photo by Duggan)

Annotated: https://www.cs.utah.edu/~elb/folklore/mel-annotated/mel-annotated.html