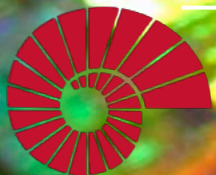


COMP201

Computer Systems & Programming

Lecture #14 – Introduction to x86-64 Assembly



KOÇ
UNIVERSITY

Aykut Erdem // Koç University // Fall 2022

Recap

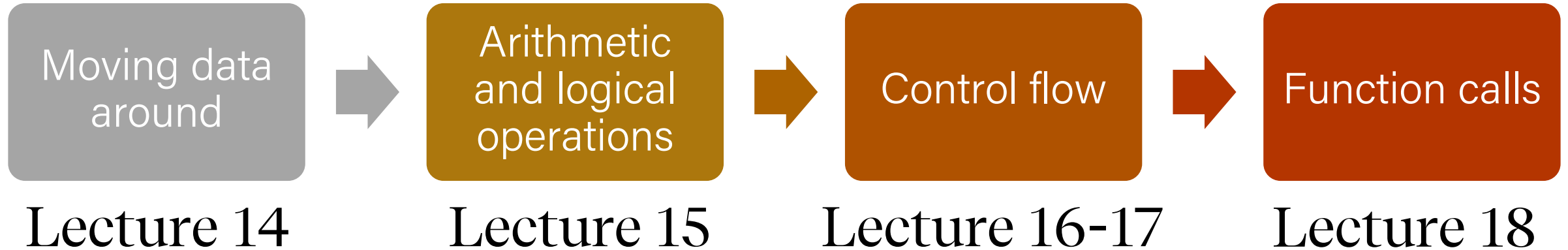
1. **Bits and Bytes** - *How can a computer represent numbers?*
2. **Chars and C-Strings** - *How can a computer represent and manipulate more complex data like text?*
3. **Pointers, Stack and Heap** – *How can we effectively manage all types of memory in our programs?*
4. **Generics** - *How can we use our knowledge of memory and data representation to write code that works with any data type?*
5. **Working with Multiple Files** – *What really happens in GCC? How to write your own Makefiles?*

Course Overview

1. **Bits and Bytes** - *How can a computer represent numbers?*
 2. **Chars and C-Strings** - *How can a computer represent and manipulate more complex data like text?*
 3. **Pointers, Stack and Heap** – *How can we effectively manage all types of memory in our programs?*
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 5. **Working with Multiple Files** – *What really happens in GCC? How to write your own Makefiles?*
-
6. **Assembly** - *How does a computer interpret and execute C programs?*
 7. **The Memory Hierarchy** – *How to improve the performance of application programs by improving their temporal and spatial locality?*
 8. **Code Optimization** – *How write C code so that a compiler can then generate efficient machine code?*
 9. **Linking** – *How static and dynamic linking work?*
 10. **Heap Allocators** - *How do core memory-allocation operations like malloc and free work?*

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

Learning Assembly



Learning Goals

- Learn what assembly language is and why it is important
- Become familiar with the format of human-readable assembly and x86
- Learn the **mov** instruction and how data moves around at the assembly level

Plan for Today

- **Overview:** GCC and Assembly
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** instruction

Disclaimer: Slides for this lecture were borrowed from
—Nick Troccoli's Stanford CS107 class

Lecture Plan

- **Overview:** GCC and Assembly
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** instruction

Bits all the way down

Data representation so far

- Integer (unsigned `int`, 2's complement signed `int`)
- Floating Points (IEEE single (`float`) and double (`double`) precision)
- `char` (ASCII)
- Address (unsigned long)
- Aggregates (arrays, `structs`)

The code itself is binary too!

- Instructions (machine encoding)

GCC

- **GCC** is the compiler that converts your human-readable code into machine-readable instructions.
- C, and other languages, are high-level abstractions we use to write code efficiently. But computers don't really understand things like data structures, variable types, etc. Compilers are the translator!
- Pure machine code is 1s and 0s – everything is bits, even your programs! But we can read it in a human-readable form called **assembly**. (Engineers used to write code in assembly before C).
- There may be multiple assembly instructions needed to encode a single C instruction.
- We're going to go behind the curtain to see what the assembly code for our programs looks like.

Lecture Plan

- Overview: GCC and Assembly
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** instruction

Demo: Looking at an Executable (objdump -d)



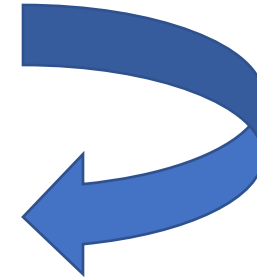
Our First Assembly

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

What does this look like in assembly?

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;  
}
```



make
objdump -d sum

00000000004005b6 <sum_array>:

```
4005b6:    ba 00 00 00 00  
4005bb:    b8 00 00 00 00  
4005c0:    eb 09  
4005c2:    48 63 ca  
4005c5:    03 04 8f  
4005c8:    83 c2 01  
4005cb:    39 f2  
4005cd:    7c f3  
4005cf:    f3 c3
```

```
mov    $0x0,%edx  
mov    $0x0,%eax  
jmp     4005cb <sum_array+0x15>  
movslq %edx,%rcx  
add     (%rdi,%rcx,4),%eax  
add     $0x1,%edx  
cmp     %esi,%edx  
jl      4005c2 <sum_array+0xc>  
repz retq
```

Our First Assembly

00000000004005b6 <sum_array>:

```
4005b6:    ba 00 00 00 00
4005bb:    b8 00 00 00 00
4005c0:    eb 09
4005c2:    48 63 ca
4005c5:    03 04 8f
4005c8:    83 c2 01
4005cb:    39 f2
4005cd:    7c f3
4005cf:    f3 c3
```

```
mov     $0x0,%edx
mov     $0x0,%eax
jmp     4005cb <sum_array+0x15>
movslq  %edx,%rcx
add     (%rdi,%rcx,4),%eax
add     $0x1,%edx
cmp     %esi,%edx
jl      4005c2 <sum_array+0xc>
repz    retq
```

Our First Assembly

00000000004005b6 <sum_array>;

This is the name of the function (same as C) and the memory address where the code for this function starts.

```
4005b6: 4a 00 00 00 00 00 mov     $0x0,%edx
4005bb: 4a 00 00 00 00 00 mov     $0x0,%eax
4005c0: 40 05 cb <sum_array+0x15>
vs1q %edx,%rcx
d (%rdi,%rcx,4),%eax
4005c8: 83 c2 01 add     $0x1,%edx
4005cb: 39 f2 cmp     %esi,%edx
4005cd: 7c f3 jl     4005c2 <sum_array+0xc>
4005cf: f3 c3 repz   retq
```

Our First Assembly

00000000004005b6 <sum_array>:

4005b6:	ba 00 00 00 00	mov	\$0x0,%edx
4005bb:	b8 00 00 00 00	mov	\$0x0,%eax
4005c0:	eb 09	jmp	4005cb <sum_array+0x15>
4005c2:	40 00 00 00	mov	4(%eax),%eax
4005c5:	00 00 00 00	mov	0(%eax),%eax
4005c8:	80 00 00 00	mov	0(%eax),%eax
4005cb:	35 12	cmp	%esi,%edx
4005cd:	7c f3	j1	4005c2 <sum_array+0xc>
4005cf:	f3 c3	repz	retq

These are the memory addresses where each of the instructions live. Sequential instructions are sequential in memory.

Our First Assembly

00000000004005b6 <sum_array>:

4005b6: ba 00 00 00 00

4005bb: b8 00 00 00 00


4005c0: eb 09

This is the assembly code:
"human-readable" versions of
each machine code instruction.

4005c0: 55 12

4005cd: 7c f3

4005cf: f3 c3

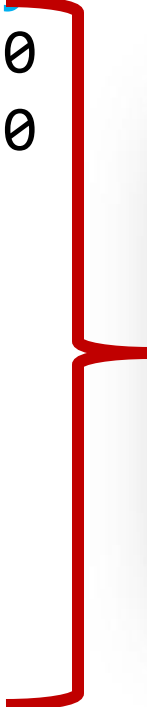


```
mov    $0x0,%edx
mov    $0x0,%eax
jmp     4005cb <sum_array+0x15>
movslq %edx,%rcx
add     (%rdi,%rcx,4),%eax
add     $0x1,%edx
cmp     %esi,%edx
jl      4005c2 <sum_array+0xc>
repz    retq
```


Our First Assembly

00000000004005b6 <sum_array>:

4005b6: ba 00 00 00 00
4005bb: b8 00 00 00 00
4005c0: eb 09
4005c2: 48 63 ca
4005c5: 03 04 8f
4005c8: 83 c2 01
4005cb: 39 f2
4005cd: 7c f3
4005cf: f3 c3



This is the machine code: raw hexadecimal instructions, representing binary as read by the computer. Different instructions may be different byte lengths.

mov \$0x0,%edx

repz retq

Our First Assembly

00000000004005b6 <sum_array>:

```
4005b6:    ba 00 00 00 00
4005bb:    b8 00 00 00 00
4005c0:    eb 09
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Our First Assembly

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```
mov    $0x0,%edx
mov    $0x0,%eax
jmp     4005cb <sum_array+0x15>
movslq %edx,%rcx
add     (%rdi,%rcx,4),%eax
add     $0x1,%edx
cmp     %esi,%edx
jle     4005c2 <sum_array+0xc>
repz retq
```



Each instruction has an operation name ("opcode").

Our First Assembly

00000000004005b6 <sum_array>:

```
4005b6:    ba 00 00 00 00
4005bb:    b8 00 00 00 00
4005c0:    eb 09
4005c2:    48 63 ca
4005c5:    03 04 8f
4005c8:    83 c2 01
4005cb:    39 f2
4005cd:    7c f3
4005cf:    f3 c3
```

```
mov    $0x0,%edx
mov    $0x0,%eax
jmp     4005cb <sum_array+0x15>
movslq %edx,%rcx
add     (%rdi,%rcx,4),%eax
add     $0x1,%edx
cmp     %esi,%edx
jl      4005c2 <sum_array+0xc>
```


Each instruction can also have arguments ("operands").

Our First Assembly

00000000004005b6 <sum_array>:

```
4005b6:    ba 00 00 00 00
4005bb:    b8 00 00 00 00
4005c0:    eb 09
4005c2:    48 63 ca
4005c5:    03 04 8f
4005c8:    83 c2 01
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4005cd:    7c f3
4005cf:    f3 c3
```

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mov    $0x0,%edx
mov    $0x0,%eax
jmp     4005cb <sum_array+0x15>
movslq %edx,%rcx
add     (%rdi,%rcx,4),%eax
add     $0x1,%edx
cmp     %esi,%edx
jl      4005c2 <sum_array+0xc>
repz retq
```



`$[number]` means a constant value, or “immediate” (e.g. 1 here).

Our First Assembly

00000000004005b6 <sum_array>:

```
4005b6:    ba 00 00 00 00
4005bb:    b8 00 00 00 00
4005c0:    eb 09
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```

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mov     $0x0,%edx
mov     $0x0,%eax
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add     (%rdi,%rcx,4),%eax
add     $0x1,%edx
cmp     %esi,%edx
jl      4005c2 <sum_array+0xc>
repz    retq
```

%[name] means a register, a storage location on the CPU (e.g. edx here).

Lecture Plan

- **Overview:** GCC and Assembly
- Demo: Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** instruction

Assembly Abstraction

- C abstracts away the low-level details of machine code. It lets us work using variables, variable types, and other higher-level abstractions.
- C and other languages let us write code that works on most machines.
- Assembly code is just bytes! No variable types, no type checking, etc.
- Assembly/machine code is processor-specific.
- What is the level of abstraction for assembly code?

Registers



%rax

Registers



`%rax`



`%rsi`



`%r8`



`%r12`



`%rbx`



`%rdi`



`%r9`



`%r13`



`%rcx`



`%rbp`



`%r10`



`%r14`



`%rdx`



`%rsp`



`%r11`



`%r15`

Registers

What is a register?

A register is a fast read/write memory slot right on the CPU that can hold variable values.

Registers are **not** located in memory.

Registers

- A **register** is a 64-bit space inside the processor.
- There are 16 registers available, each with a unique name.
- Registers are like “scratch paper” for the processor. Data being calculated or manipulated is moved to registers first. Operations are performed on registers.
- Registers also hold parameters and return values for functions.
- Registers are extremely *fast* memory!
- Processor instructions consist mostly of moving data into/out of registers and performing arithmetic on them. This is the level of logic your program must be in to execute!

Machine-Level Code

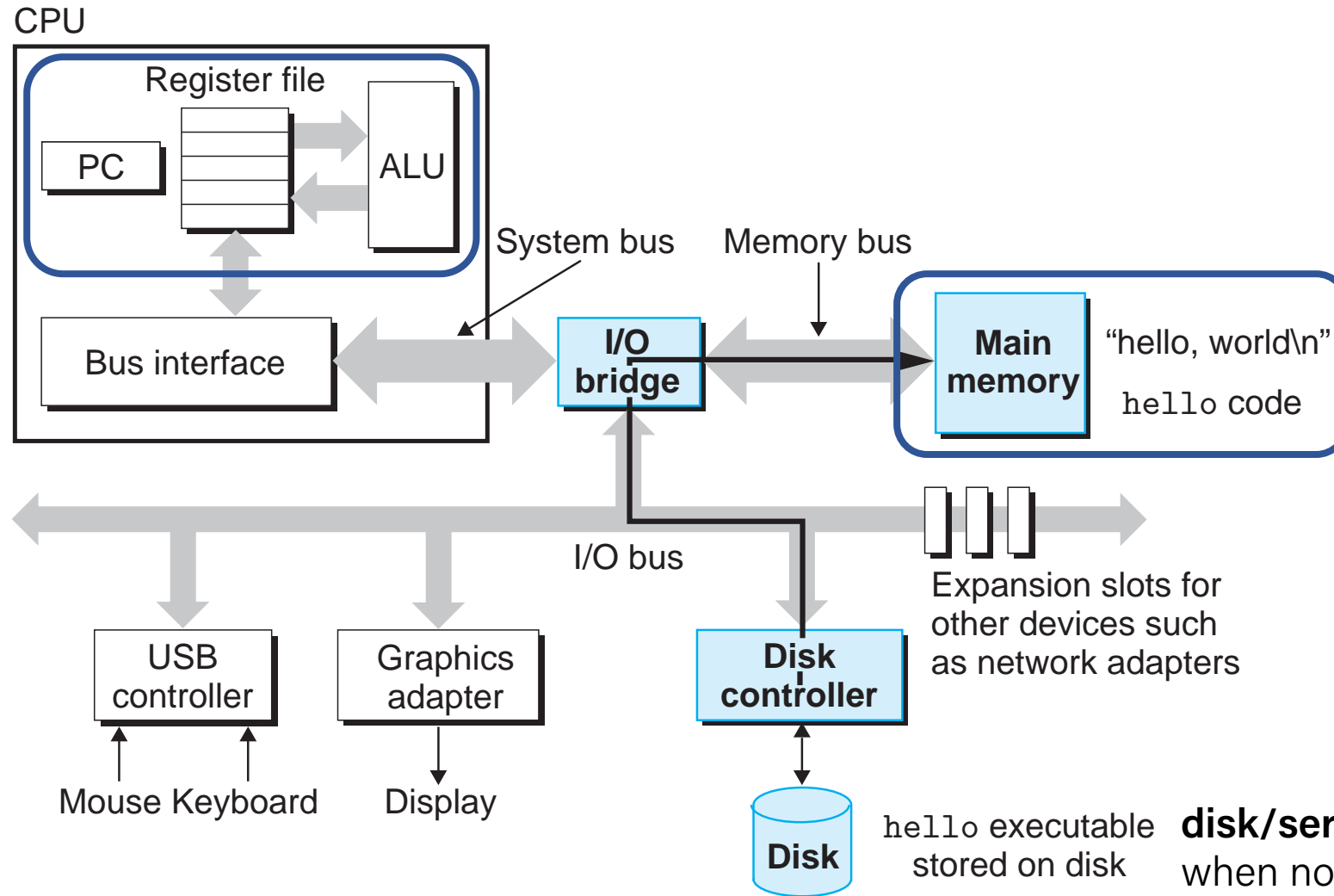
Assembly instructions manipulate these registers. For example:

- One instruction adds two numbers in registers
- One instruction transfers data from a register to memory
- One instruction transfers data from memory to a register

Computer architecture

registers accessed by name

ALU is main workhorse of CPU



memory needed for program execution (stack, heap, etc.) accessed by address

hello executable stored on disk **disk/server** stores program when not executing

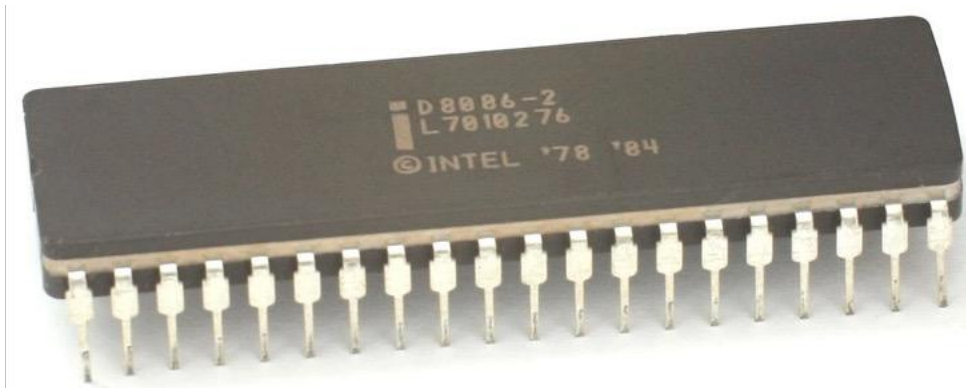
GCC And Assembly

- GCC compiles your program – it lays out memory on the stack and heap and generates assembly instructions to access and do calculations on those memory locations.
- Here's what the “assembly-level abstraction” of C code might look like:

C	Assembly Abstraction
int sum = x + y;	<i>1) Copy x into register 1 2) Copy y into register 2 3) Add register 2 to register 1 4) Write register 1 to memory for sum</i>

Assembly

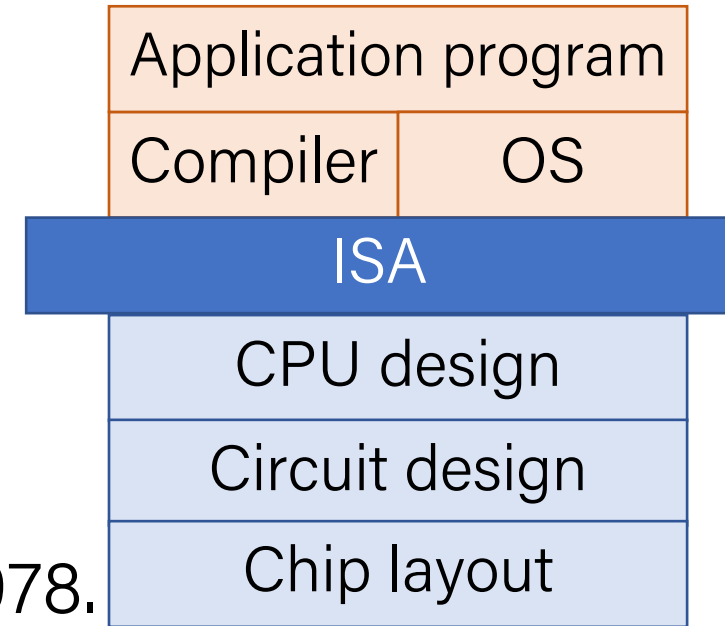
- We are going to learn the **x86-64** instruction set architecture. This instruction set is used by Intel and AMD processors.
- There are many other instruction sets: ARM, MIPS, etc.



Instruction set architecture (ISA)

A contract between program/compiler and hardware:

- Defines operations that the processor (CPU) can execute
- Data read/write/transfer operations
- Control mechanisms



Intel originally designed their instruction set back in 1978.

- Legacy support is a huge issue for x86-64
- Originally 16-bit processor, then 32 bit, now 64 bit.
These design choices dictated the register sizes
(and even register/instruction names).



Lecture Plan

- **Overview:** GCC and Assembly
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** instruction

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***)

\$0x104

%rbx

Direct address **0x6005c0**

Operand Forms: Immediate

mov **\$0x104,** _____




*Copy the value
0x104 into some
destination.*

Operand Forms: Registers

mov

%rbx, _____


*Copy the value in
register %rbx into
some destination.*



mov

_____, %rbx


*Copy the value from
some source into
register %rbx.*



Operand Forms: Absolute Addresses


mov **0x104, _____**

Copy the value at address 0x104 into some destination.



mov **_____, 0x104**

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



Practice #1: Operand Forms


What are the results of the following move instructions (executed separately)? For this problem, assume the value 5 is stored at address 0x42, and the value 8 is stored in %rbx.

1. **mov \$0x42,%rax** Move 0x42 into %rax
2. **mov 0x42,%rax** Move 5 into %rax
3. **mov %rbx,0x55** Move 8 to address 0x55

Operand Forms: Indirect

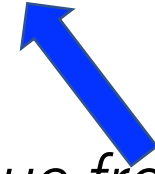
mov **(%rbx), _____**

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



mov **_____, (%rbx)**

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



Operand Forms: Base + Displacement

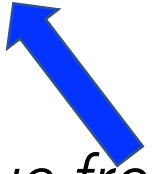
mov **0x10(%rax),** _____

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



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 #2: 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. <code>mov</code> | <code>\$0x42, (%rax)</code> | Move <code>0x42</code> to memory address <code>0x100</code> |
| 2. <code>mov</code> | <code>4(%rax), %rcx</code> | Move <code>0xAB</code> into <code>%rcx</code> |
| 3. <code>mov</code> | <code>9(%rax, %rdx), %rcx</code> | Move <code>0x11</code> into <code>%rcx</code> |

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

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), _____

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

mov

_____, (, %rdx, 4)


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

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

is equivalent to...

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

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)

Memory Location Syntax

Syntax	Meaning
<code>0x104</code>	Address <code>0x104</code> (no <code>\$</code>)
<code>(%rax)</code>	What's in <code>%rax</code>
<code>4(%rax)</code>	What's in <code>%rax</code> , plus 4
<code>(%rax, %rdx)</code>	Sum of what's in <code>%rax</code> and <code>%rdx</code>
<code>4(%rax, %rdx)</code>	Sum of values in <code>%rax</code> and <code>%rdx</code> , plus 4
<code>(, %rcx, 4)</code>	What's in <code>%rcx</code> , times 4 (multiplier can be 1, 2, 4, 8)
<code>(%rax, %rcx, 2)</code>	What's in <code>%rax</code> , plus 2 times what's in <code>%rcx</code>
<code>8(%rax, %rcx, 2)</code>	What's in <code>%rax</code> , plus 2 times what's in <code>%rcx</code> , 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 #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
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`

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

Goals of indirect addressing: C

Why are there so many forms of indirect addressing?

We see these indirect addressing paradigms in C as well!

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;  
}
```

We're 1/4th of the way to understanding assembly!
What looks understandable right now?

Some notes:

- Registers store addresses and values
- `mov src, dst` ***copies*** value into `dst`
- `sizeof(int)` is 4
- Instructions executed sequentially

00000000004005b6 <sum_array>:

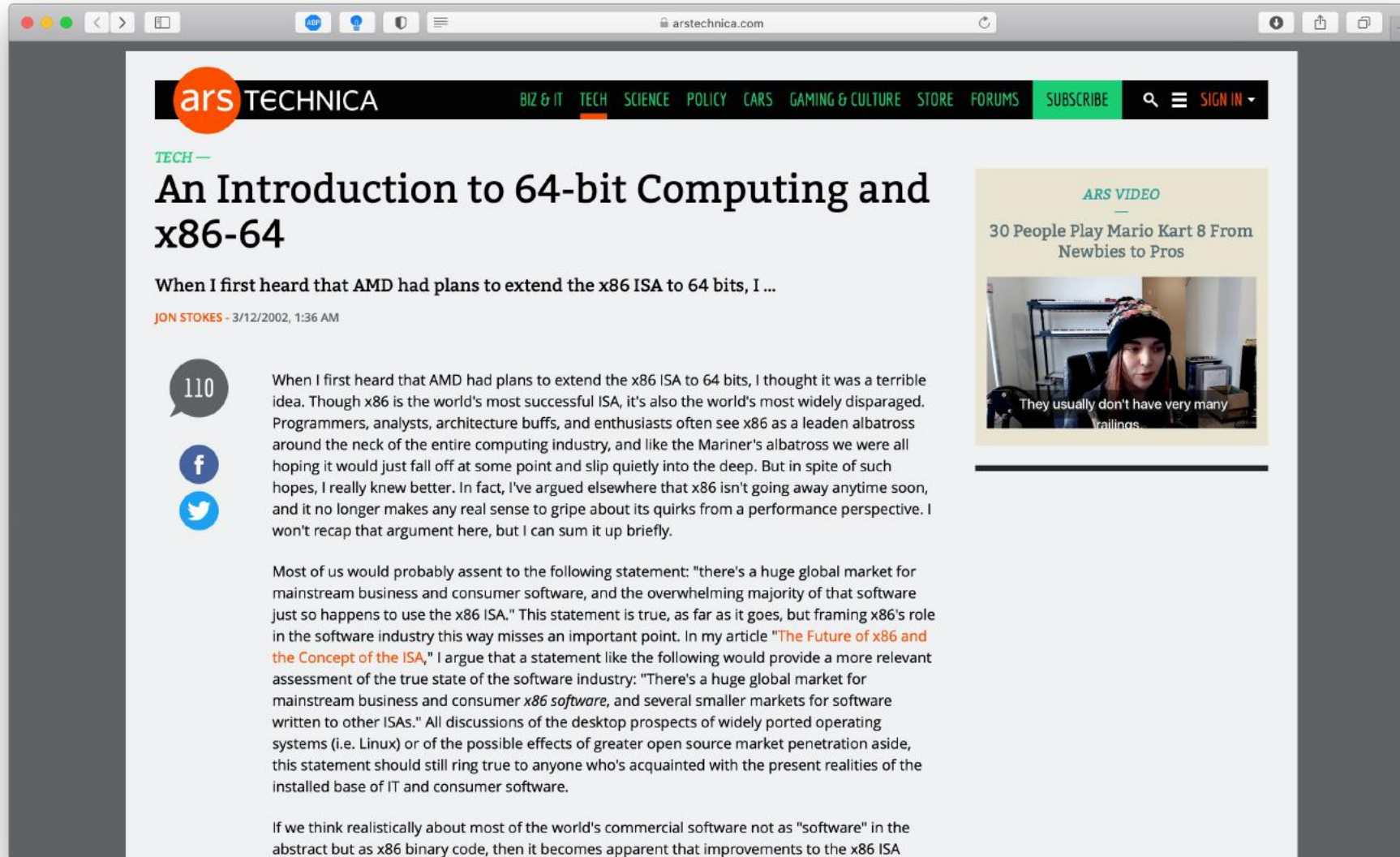
```
4005b6:  ba 00 00 00 00  
4005bb:  b8 00 00 00 00  
4005c0:  eb 09  
4005c2:  48 63 ca  
4005c5:  03 04 8f  
4005c8:  82 c2 01
```

We'll come back to this
example in future lectures!

```
mov    $0x0,%edx  
mov    $0x0,%eax  
jmp     4005cb <sum_array+0x15>  
movslq %edx,%rcx  
add     (%rdi,%rcx,4),%eax  
add     $0x1,%edx  
cmp     %esi,%edx  
jl      4005c2 <sum_array+0xc>  
repz   retq
```

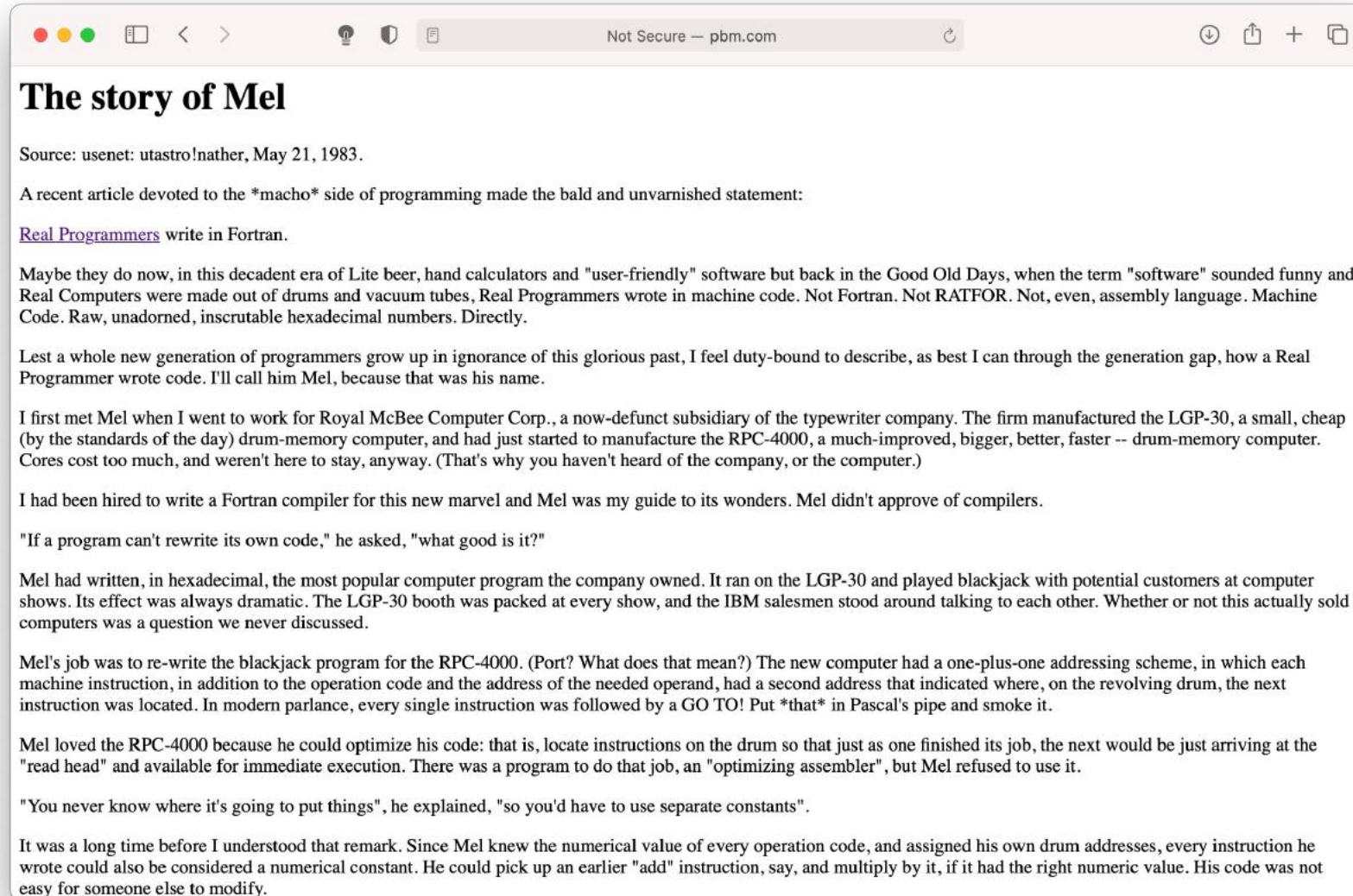


Additional Reading



<https://arstechnica.com/gadgets/2002/03/an-introduction-to-64-bit-computing-and-x86-64/>

Additional Reading



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

Extra Practice

Extra Practice

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

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

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

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

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

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)
```

Recap

- **Overview:** GCC and Assembly
- **Demo:** Looking at an executable
- Registers and The Assembly Level of Abstraction
- The **mov** instruction

Next time: *diving deeper into assembly*