CS107, Lecture 14

Introduction to Assembly

Reading: B&O 3.1-3.4

Ed Discussion: https://edstem.org/us/courses/65949/discussion/5552297

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

Course Overview

1. **Bits and Bytes -** *How can a computer represent integer 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?*

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5. **Assembly -** *How does a computer interpret and execute C programs?*
6. **Heap Allocators -** *How do core memory-allocation operations like malloc and free work?*

<u>CS107 Topic 5</u>: How does a computer interpret and execute C programs?

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 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.

Bits all the way down

Data representation so far

- Integer (`unsigned int`, 2's complement signed `int`)
- `char` (ASCII)
- Address (unsigned long)
- Aggregates (arrays, `structs`)

The code itself is binary too!

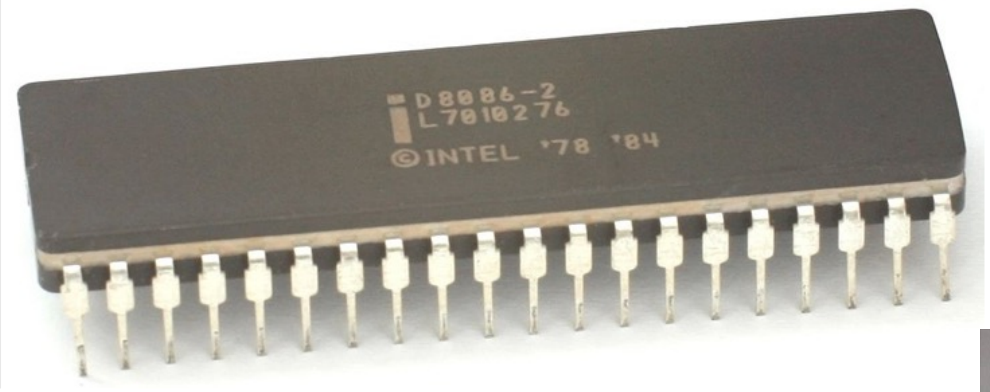
- Instructions (machine code)

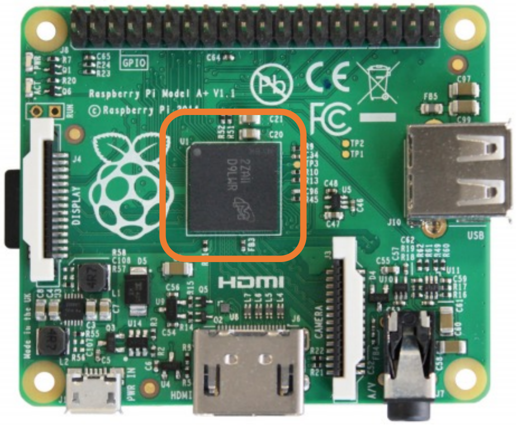
gcc

- **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.

Central Processing Units (CPUs)

Intel 8086, 16-bit
microprocessor
($86.65, 1978)

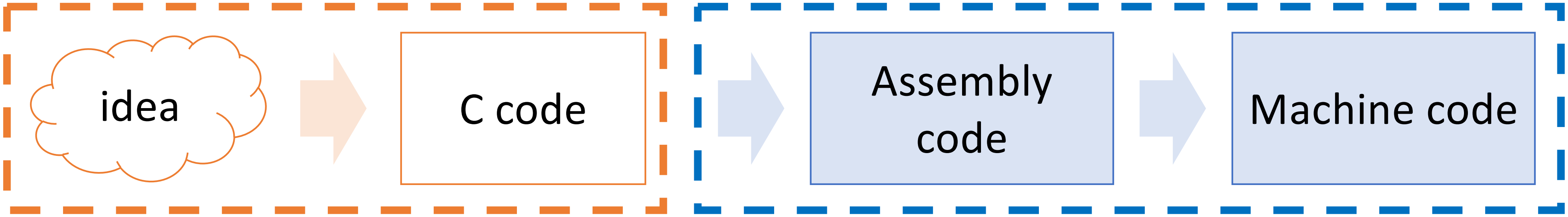




Raspberry Pi BCM2836
32-bit **ARM** microprocessor
($35 for everything, 2015)

Intel Core i9-9900K 64-bit
8-core multi-core processor
($449, 2018)

Why are we reading assembly?



Programmer-generated

gcc (compiler+assembler) generated

Main goal: Information retrieval

- We will not be writing assembly! (that's the compiler's job)
- Rather, we want to translate the assembly ***back*** into our C code.
- Knowing how our C code is converted into machine instructions gives us insight into how to write cleaner, more efficient code.

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
```

```
0000000000401136 <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
```

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:  b8 00 00 00 00        mov    $0x0,%eax
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  401151:  c3                    retq
```

Our First Assembly

```
0000000000401136 <sum_array>:
   401136:   b8 00 00 00 00          mov     $0x0,%eax
   40113b:   ba 00 00 00 00          mov     $0x0,%edx
                                       p     %esi,%eax
                                       e     40114f <sum_array+0x19>
                                    vslq     %eax,%rcx
                                       d     (%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
```

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

Our First Assembly

```
0000000000401136 <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                                  _array+0x19>
  401144: 48
  401147: 03                                 4),%edx
  40114a: 83
  40114d: eb f1                   jmp    401140 <sum_array+0xa>
  40114f: 89 d0                   mov    %edx,%eax
  401151: c3                      retq
```

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

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:  b8 00 00 00 00        mov    $0x0,%eax
  40113b:  ba 00 00 00 00        mov    $0x0,%edx
                                 cmp    %esi,%eax
                                 jge    40114f <sum_array+0x19>
                                 movslq %eax,%rcx
                                 add    (%rdi,%rcx,4),%edx
                                 add    $0x1,%eax
  40114d:  eb f1                 jmp    401140 <sum_array+0xa>
  40114f:  89 d0                 mov    %edx,%eax
  401151:  c3                    retq
```

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

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:   b8 00 00 00 00          mov     $0x0,%eax
  40113b:   ba 00 00 00 00
  401140:   39 f0
  401142:   7d 0b
  401144:   48 63 c8
  401147:   03 14 8f
  40114a:   83 c0 01
  40114d:   eb f1
  40114f:   89 d0                   mov     %edx,%eax
  401151:   c3                      retq
```

This is the machine code: raw hexadecimal instructions, representing binary as read by the computer. Different instructions require a varying number of bytes.

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:   b8 00 00 00 00          mov    $0x0,%eax
  40113b:   ba 00 00 00 00          mov    $0x0,%edx
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```

Our First Assembly

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  40114d:   eb f1                   jmp    401140 <sum_array+0xa>
  40114f:   89 d0                   mov    %edx,%eax
  401151:   c3                      retq
```

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

Our First Assembly

```
0000000000401136 <sum_array>:
  401136:   b8 00 00 00 00          mov    $0x0,%eax
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  40114a:   83 c0 01                add    $0x1,%eax
  40114d:   eb f1                   jmp    401140 <sum_array+0xa>
  40114f:   89 d0                   mov    %edx,%eax
  401151:   c3
```

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

Our First Assembly

```
0000000000401136 <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
```

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

Our First Assembly

```
0000000000401136 <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>
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  40114d:  eb f1                  jmp     401140 <sum_array+0xa>
  40114f:  89 d0                  mov     %edx,%eax
  401151:  c3                     retq
```

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

🌟 Keep a resource guide handy 🌟

- https://web.stanford.edu/class/cs107/resources/x86-64-reference.pdf
- B&O book:
  - Canvas -> Files
    -> Bryant_OHallaron_ch3.1-3.8.pdf
- It’s like learning how to read—though not speak—a new language!

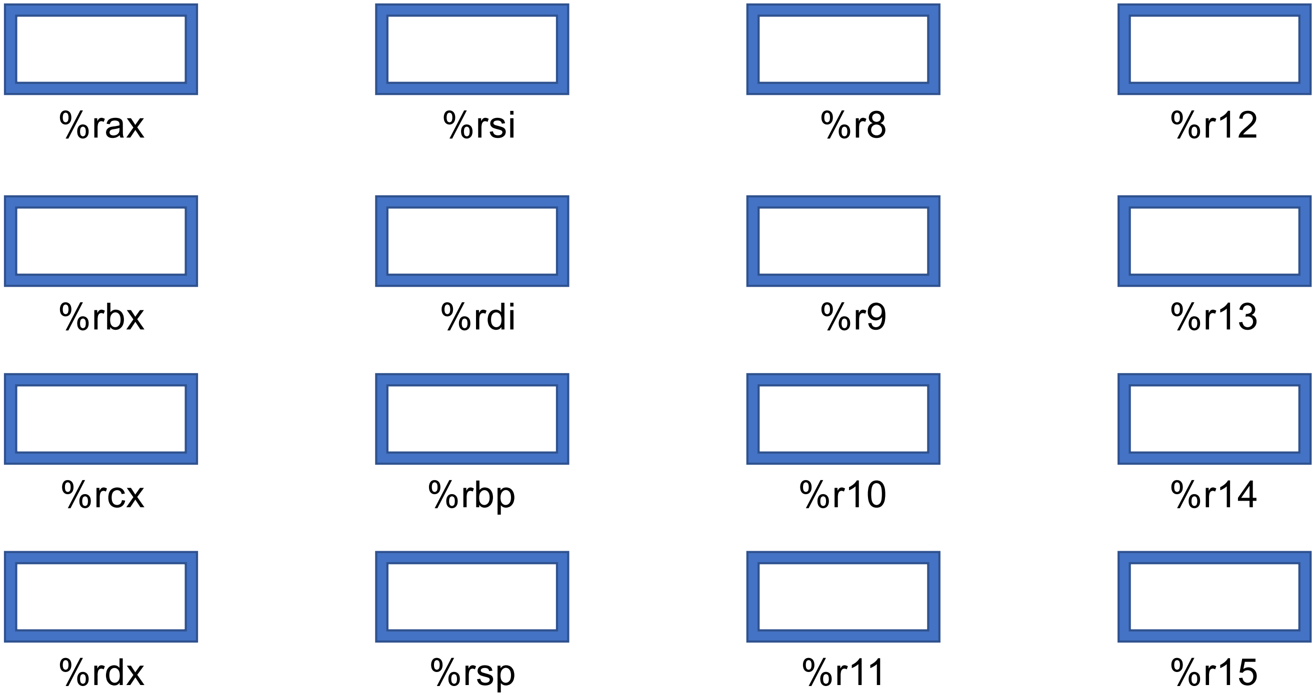
Assembly Abstraction

- 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
%rbx
%rcx
%rdx

%rsi
%rdi
%rbp
%rsp

%r8
%r9
%r10
%r11

%r12
%r13
%r14
%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, each with a unique name.
- Registers are like "scratch paper" for the processor. Data being accessed or manipulated are first moved into registers. Most ALU operations—that is, arithmetic-logic unit operations—can only act on values stored in 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 operations on them. This is the level of logic your program must be in to execute!

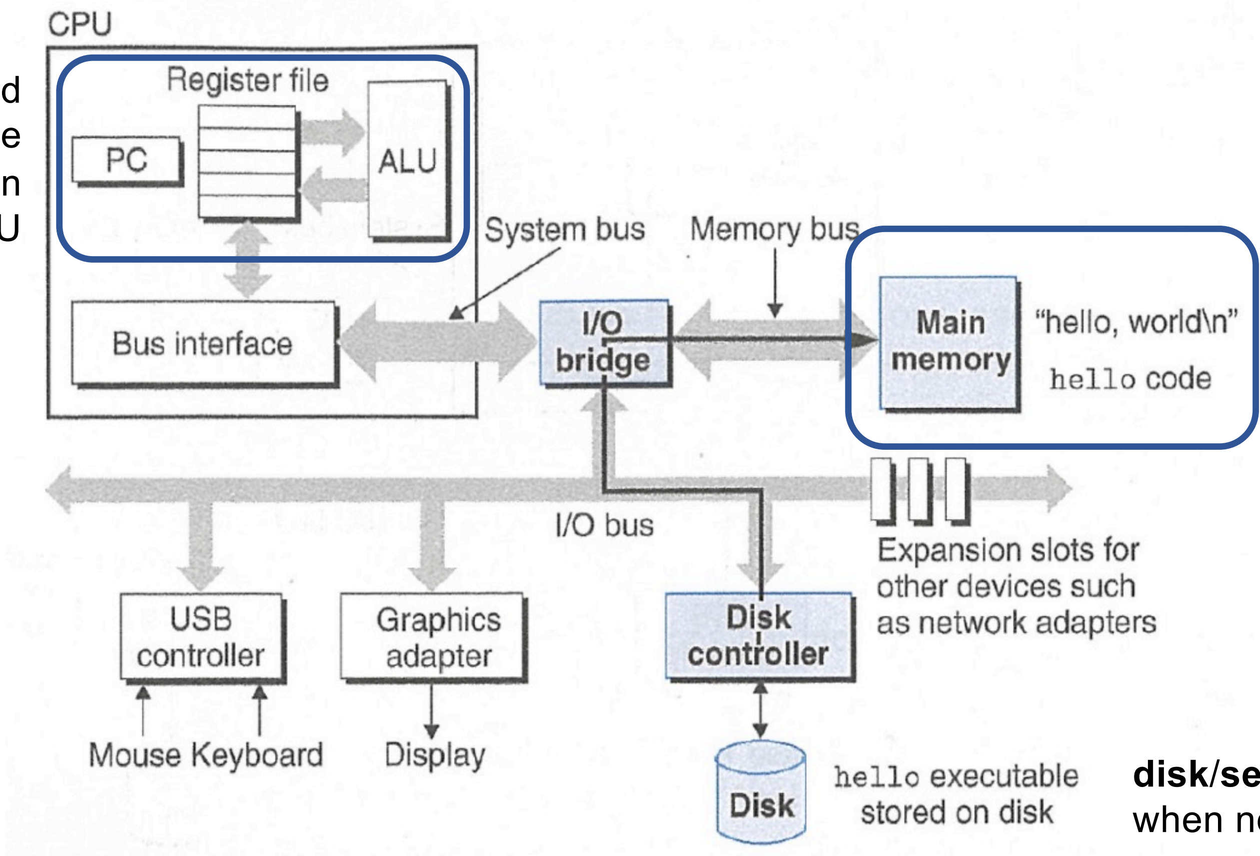
Machine-Level Code

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

disk/**server** stores program when not executing

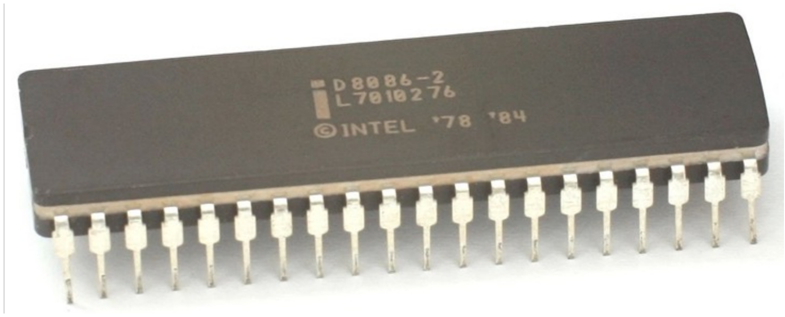
GCC And Assembly

- 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;`	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

Assembly

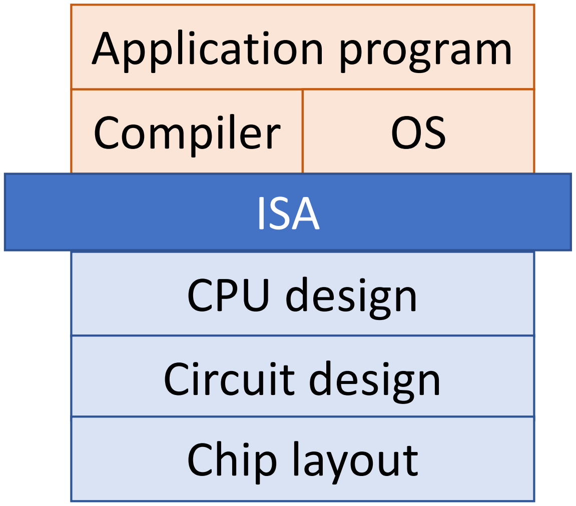
- We are going to learn the **x86-64** instruction set architecture. This instruction set is used by Intel and AMD processors.
- There are many other instruction sets: ARM, MIPS, etc.



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



Application program

Compiler

OS

ISA

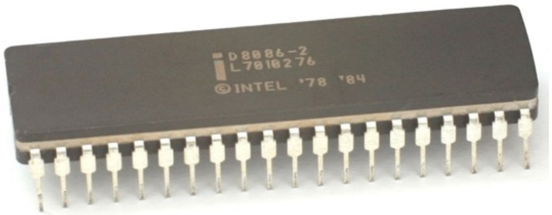
CPU design

Circuit design

Chip layout

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).



mov

The **`mov`** instruction copies bytes from one place to another;
it is like the assignment operator (=) in C, though the arguments are reversed.

```
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.

Practice: 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

2. mov    0x42,%rax

3. mov    %rbx,0x55
```

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 ***<u>0x10 plus</u>*** *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 ***<u>0x10 plus</u>*** *the values in registers %rax and %rdx).*

Practice: 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*, *0xAB* is stored at address *0x104*, *0x100* is stored in register %rax and *0x3* is stored in %rdx.

```
1. mov   $0x42,(%rax)
2. mov   4(%rax),%rcx
3. mov   9(%rax,%rdx),%rcx
```

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

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 (**<u>4 times</u>** 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 (**<u>4 times</u>** 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

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

is equivalent to…

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

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)

Operand Forms

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

`Imm(`r_b`, `r_i`, s)` is equivalent to address **`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 on our 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        mov    $0x0,%edx
  4005bb:    b8 00 00 00 00        mov    $0x0,%eax
  4005c0:    eb 09                 jmp    4005cb <sum_array+0x15>
  4005c2:    48 63 ca              movslq %edx,%rcx
  4005c5:    03 04 8f              add    (%rdi,%rcx,4),%eax
  4005c8:    83 c2 01              add    $0x1,%edx
                                   cmp    %esi,%edx
                                   jl     4005c2 <sum_array+0xc>
                                   repz retq
```

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

From Assembly to C

Spend a few minutes thinking about the main paradigms of the `mov` instruction.

- What might be the equivalent C-like operation?
- Examples (note %r__ registers are 64-bit):

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

From Assembly to C

Spend a few minutes thinking about the main paradigms of the `mov` instruction.

- What might be the equivalent C-like operation?
- Examples (note %r__ registers are 64-bit):

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!