CS107, Lecture 12
Assembly: Control Flow

Reading: B&O 3.6

CS107 Topic 5: 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 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

Moving data around	→	Arithmetic and logical operations	→	Control flow	→	Function calls
Lecture 10		**Lecture 11**		**This Lecture**		**Lecture 13**

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

Learning Goals

- Understand how assembly implements loops and control flow
- Learn about how assembly stores comparison and operation results in condition codes

Lecture Plan

- Recap: Assembly So Far
- Assembly Execution and %rip
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

Lecture Plan

- **Recap: Assembly So Far**
- Assembly Execution and %rip
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

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***)

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.

Arithmetic and Logical Operators

- Many instructions share the same address operand forms that **mov** uses.
  - Eg. 7(%rax, %rcx, 2).
- E.g. **add**, **sub**, **imul**, etc.

Reverse Engineering 2

```
int elem_arithmetic(int nums[], int y) {
    int z = nums[___?___] * ___?___;
    z -= ___?___;
    z >>= ___?___;
    return ___?___;
}
----------
// nums in %rdi, y in %esi
elem_arithmetic:
  movl %esi, %eax
  imull (%rdi), %eax
  subl 4(%rdi), %eax
  sarl $2, %eax
  addl $2, %eax
  ret
```

Reverse Engineering 2

```
int elem_arithmetic(int nums[], int y) {
    int z = nums[___?___] * ___?___;
    z -= ___?___;
    z >>= ___?___;
    return ___?___;
}
----------
// nums in %rdi, y in %esi
elem_arithmetic:
  movl %esi, %eax          // copy y into %eax
  imull (%rdi), %eax       // multiply %eax by nums[0]
  subl 4(%rdi), %eax       // subtract nums[1] from %eax
  sarl $2, %eax            // shift %eax right by 2
  addl $2, %eax            // add 2 to %eax
  ret
```

Reverse Engineering 2

```
int elem_arithmetic(int nums[], int y) {
    int z = nums[0] * y;
    z -= nums[1];
    z >>= 2;
    return z + 2;
}
----------
// nums in %rdi, y in %esi
elem_arithmetic:
  movl %esi, %eax           // copy y into %eax
  imull (%rdi), %eax        // multiply %eax by nums[0]
  subl 4(%rdi), %eax        // subtract nums[1] from %eax
  sarl $2, %eax             // shift %eax right by 2
  addl $2, %eax             // add 2 to %eax
  ret
```

Lecture Plan

- Recap: Assembly So Far
- **Assembly Execution and %rip**
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

Executing Instructions

What does it mean for a program to execute?

Executing Instructions

So far:

- Program values can be stored in memory or registers.
- Assembly instructions read/write values back and forth between registers (on the CPU) and memory.
- Assembly instructions are also stored in memory.

Today:

- **Who controls the instructions**?
  How do we know what to do now or next?

Answer:

- The **program counter** (PC), %rip.

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

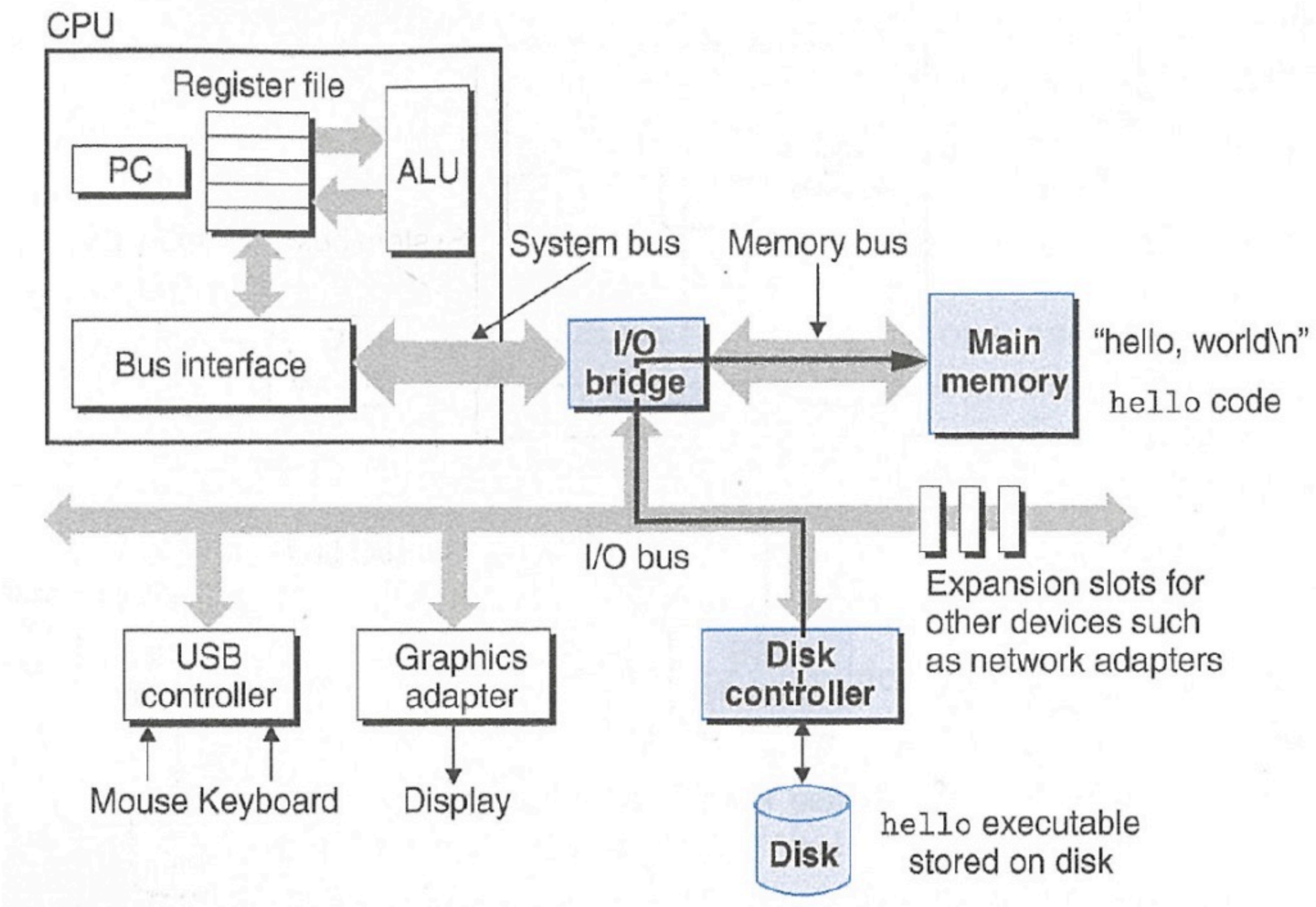
Register Responsibilities

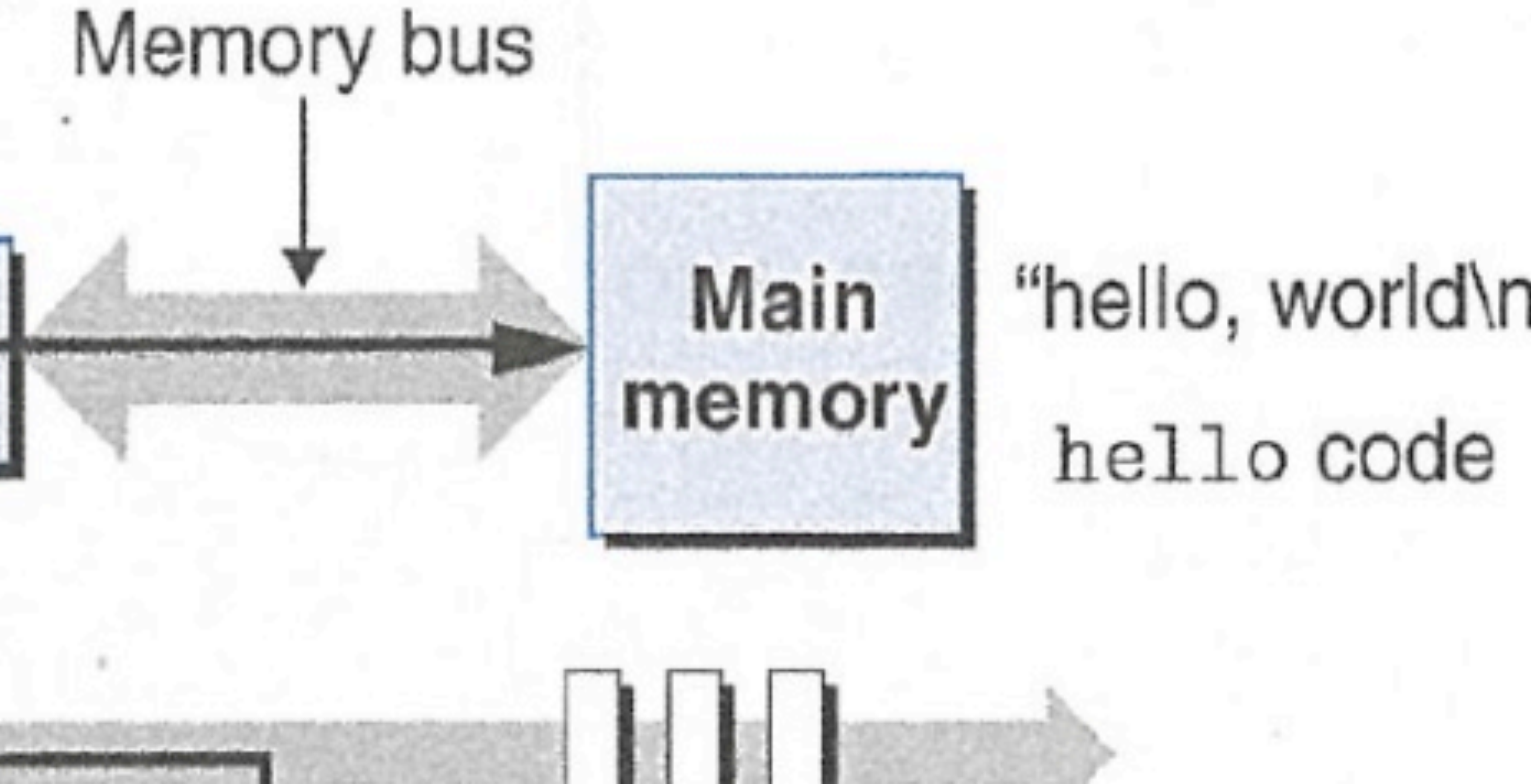
Some registers take on special responsibilities during program execution.

- **%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

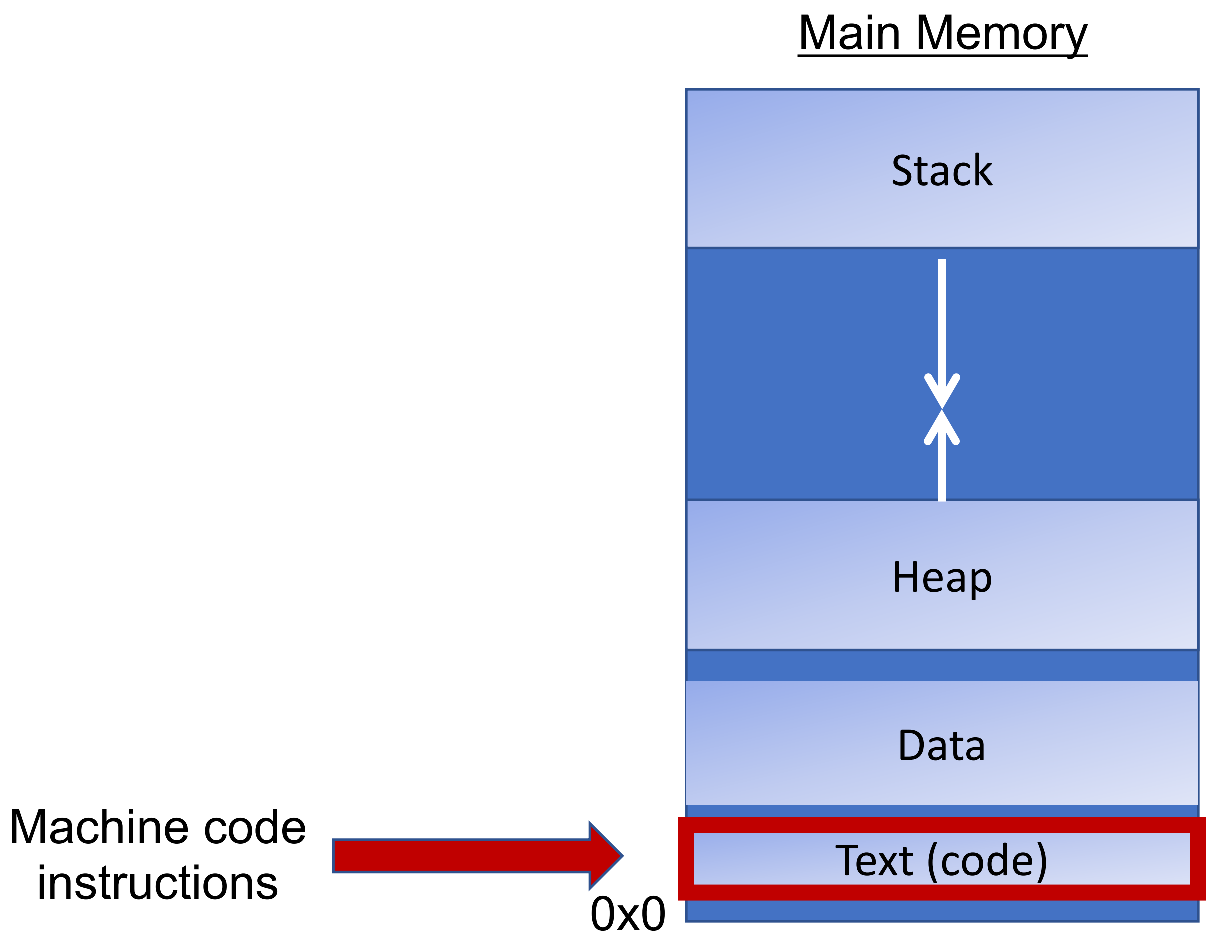
See the x86-64 Guide and Reference Sheet on the Resources webpage for more!

Instructions Are Just Bytes!




Memory bus
Main memory
“hello, world\n
hello code

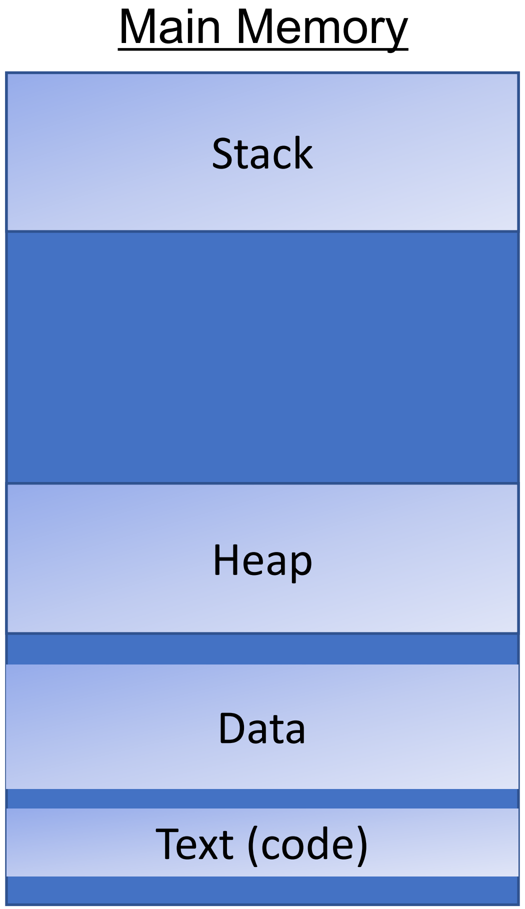
Instructions Are Just Bytes!



%ri

```
00000000004004ed <loop>:
4004ed: 55                    push   %rbp
4004ee: 48 89 e5              mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
4004fc: eb fa                 jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55



%rip

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

`0x4004ed`

%rip

%rip

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

`0x4004ee`

%rip

%rip

```
0000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

0x4004f1

%rip

%rip

```
00000000004004ed <loop>:
4004ed: 55                    push   %rbp
4004ee: 48 89 e5              mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00  movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01           addl   $0x1,-0x4(%rbp)
4004fc: eb fa                 jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

0x4004f8

%rip

%rip

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

The **program counter** (PC), known as %rip in x86-64, stores the address in memory of the ***next instruction*** to be executed.

0x4004fc

%rip

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

%rip

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

Special hardware sets the program counter to the next instruction:

%rip += size of bytes of current instruction

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

```
0x4004fc
```
%rip

Going In Circles

- How can we use this representation of execution to represent e.g. a **loop**?
- **Key Idea:** we can ”interfere” with **%rip** and set it back to an earlier instruction!

Jump!

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **jmp** instruction is an **unconditional jump** that sets the program counter to the **jump target** (the operand).

0x4004fc

%rip

Jump!

```
00000000004004ed <loop>:
4004ed: 55                   push   %rbp
4004ee: 48 89 e5             mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00 movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01          addl   $0x1,-0x4(%rbp)
4004fc: eb fa                jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **jmp** instruction is an **unconditional jump** that sets the program counter to the **jump target** (the operand).

`0x4004fc`

`%rip`

Jump!

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **jmp** instruction is an **unconditional jump** that sets the program counter to the **jump target** (the operand).

`0x4004fc`

`%rip`

Jump!

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

The **jmp** instruction is an **unconditional jump** that sets the program counter to the **jump target** (the operand).

`0x4004fc`

`%rip`

Jump!

```
00000000004004ed <loop>:
4004ed: 55                      push   %rbp
4004ee: 48 89 e5                mov    %rsp,%rbp
4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
4004f8: 83 45 fc 01             addl   $0x1,-0x4(%rbp)
4004fc: eb fa                   jmp    4004f8 <loop+0xb>
```

This assembly represents an infinite loop in C!

```
while (true) {…}
```

```
0x4004fc
```

%rip

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

jmp

The **jmp** instruction jumps to another instruction in the assembly code ("Unconditional Jump").

```
jmp Label        (Direct Jump)
jmp *Operand     (Indirect Jump)
```

The destination can be hardcoded into the instruction (direct jump):

```
jmp 404f8 <loop+0xb>   # jump to instruction at 0x404f8
```

The destination can also be one of the usual operand forms (indirect jump):

```
jmp *%rax        # jump to instruction at address in %rax
```

“Interfering” with %rip

1. How do we repeat instructions in a loop?

```
jmp [target]
```

- A 1-step unconditional jump (always jump when we execute this instruction)

What if we want a **conditional jump**?

Lecture Plan

- Recap: Assembly So Far
- Assembly Execution and %rip
- **Control Flow Mechanics**
  - Condition Codes
  - Assembly Instructions
- If statements
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

Control

- In C, we have control flow statements like **if**, **else**, **while**, **for**, etc. to write programs that are more expressive than just one instruction following another.
- This is *conditional execution of statements*: executing statements if one condition is true, executing other statements if one condition is false, etc.
- How is this represented in assembly?

Control

```
if (x > y) {
    // a
} else {
    // b
}
```

In Assembly:

1. **Calculate the condition result**
2. **Based on the result, go to a or b**

Control

- In assembly, it takes more than one instruction to do these two steps.
- Most often: 1 instruction to calculate the condition, 1 to conditionally jump

Common Pattern:

1. `cmp S1, S2` // compare two values
2. **je [target]** *or* **jne [target]** *or* **jl [target]** *or* … // conditionally jump

"jump if equal"

"jump if not equal"

"jump if less than"

Conditional Jumps

There are also variants of **jmp** that jump only if certain conditions are true ("Conditional Jump"). The jump location for these must be hardcoded into the instruction.

Instruction	Synonym	Set Condition
`je` *`Label`*	`jz`	Equal / zero
`jne` *`Label`*	`jnz`	Not equal / not zero
`js` *`Label`*		Negative
`jns` *`Label`*		Nonnegative
`jg` *`Label`*	`jnle`	Greater (signed >)
`jge` *`Label`*	`jnl`	Greater or equal (signed >=)
`jl` *`Label`*	`jnge`	Less (signed <)
`jle` *`Label`*	`jng`	Less or equal (signed <=)
`ja` *`Label`*	`jnbe`	Above (unsigned >)
`jae` *`Label`*	`jnb`	Above or equal (unsigned >=)
`jb` *`Label`*	`jnae`	Below (unsigned <)
`jbe` *`Label`*	`jna`	Below or equal (unsigned <=)

Control

Read **cmp S1,S2** as *"compare S2 to S1"*:

```
// Jump if %edi > 2
cmp $2, %edi
jg [target]
```

```
// Jump if %edi == 4
cmp $4, %edi
je [target]
```

```
// Jump if %edi != 3
cmp $3, %edi
jne [target]
```

```
// Jump if %edi <= 1
cmp $1, %edi
jle [target]
```

Wait a minute – how does the jump instruction know anything about the compared values in the earlier instruction?

Control

- The CPU has special registers called *condition codes* that are like “global variables”. They *automatically* keep track of information about the most recent arithmetic or logical operation.
  - **cmp** compares via calculation (subtraction) and info is stored in the condition codes
  - conditional jump instructions look at these condition codes to know whether to jump
- What exactly are the condition codes? How do they store this information?

Condition Codes

Alongside normal registers, the CPU also has single-bit *condition code* registers. They store the results of the most recent arithmetic or logical operation.

Most common condition codes:

- **CF:** Carry flag. The most recent operation generated a carry out of the most significant bit. Used to detect overflow for unsigned operations.
- **ZF:** Zero flag. The most recent operation yielded zero.
- **SF:** Sign flag. The most recent operation yielded a negative value.
- **OF:** Overflow flag. The most recent operation caused a two's-complement overflow-either negative or positive.

Setting Condition Codes

The **cmp** instruction is like the subtraction instruction, but it does not store the result anywhere. It just sets condition codes. (**Note** the operand order!)

```
CMP S1, S2          S2 – S1
```

Instruction	Description
`cmpb`	Compare byte
`cmpw`	Compare word
`cmpl`	Compare double word
`cmpq`	Compare quad word

Control

Read **cmp S1,S2** as *"compare S2 to S1"*. It calculates S2 – S1 and updates the condition codes with the result.

```
// Jump if %edi > 2
// calculates %edi - 2
cmp $2, %edi
jg [target]
```

```
// Jump if %edi == 4
// calculates %edi - 4
cmp $4, %edi
je [target]
```

```
// Jump if %edi != 3
// calculates %edi - 3
cmp $3, %edi
jne [target]
```

```
// Jump if %edi <= 1
// calculates %edi - 1
cmp $1, %edi
jle [target]
```

How to remember cmp/jmp

- `CMP S1, S2` is `S2 – S1` (just sets condition codes). **But generally**:

```
cmp S1, S2
jg  …
```

⟺ **S2** > S1 ⟺ **S2** - S1 > 0

Conditional Jumps

Conditional jumps can look at subsets of the condition codes in order to check their condition of interest.

Instruction	Synonym	Set Condition
`je` *Label*	`jz`	Equal / zero (ZF = 1)
`jne` *Label*	`jnz`	Not equal / not zero (ZF = 0)
`js` *Label*		Negative (SF = 1)
`jns` *Label*		Nonnegative (SF = 0)
`jg` *Label*	`jnle`	Greater (signed >) (ZF = 0 and SF = OF)
`jge` *Label*	`jnl`	Greater or equal (signed >=) (SF = OF)
`jl` *Label*	`jnge`	Less (signed <) (SF != OF)
`jle` *Label*	`jng`	Less or equal (signed <=) (ZF = 1 or SF! = OF)
`ja` *Label*	`jnbe`	Above (unsigned >) (CF = 0 and ZF = 0)
`jae` *Label*	`jnb`	Above or equal (unsigned >=) (CF = 0)
`jb` *Label*	`jnae`	Below (unsigned <) (CF = 1)
`jbe` *Label*	`jna`	Below or equal (unsigned <=) (CF = 1 or ZF = 1)

Setting Condition Codes

The **test** instruction is like **cmp**, but for AND. It does not store the & result anywhere. It just sets condition codes.

`TEST S1, S2`   `S2 & S1`

Instruction	Description
`testb`	Test byte
`testw`	Test word
`testl`	Test double word
`testq`	Test quad word

Cool trick: if we pass the same value for both operands, we can check the sign of that value using the **Sign Flag** and **Zero Flag** condition codes!

The test Instruction

- `TEST S1, S2` is `S2 & S1`

```
test %edi, %edi
jns  …
```

`%edi & %edi is nonnegative`

`%edi is nonnegative`

Condition Codes

- Previously-discussed arithmetic and logical instructions update these flags. **lea** does not (it was intended only for address computations).
- Logical operations (**xor**, etc.) set carry and overflow flags to zero.
- Shift operations set the carry flag to the last bit shifted out and set the overflow flag to zero.
- For more complicated reasons, **inc** and **dec** set the overflow and zero flags, but leave the carry flag unchanged.

Exercise 1: Conditional jump

```
je target              jump if ZF is 1
```

Let `%edi` store 0x10. Will we jump in the following cases?

%edi `0x10`

1. ```
   cmp $0x10,%edi
   je  40056f
   add  $0x1,%edi
   ```

2. ```
   test $0x10,%edi
   je   40056f
   add  $0x1,%edi
   ```

Exercise 1: Conditional jump

`je target` jump if ZF is 1

Let `%edi` store 0x10. Will we jump in the following cases?

%edi	0x10

1. ```
   cmp $0x10,%edi
   je  40056f
   add  $0x1,%edi
   ```
   S2 - S1 == 0, so jump

2. ```
   test $0x10,%edi
   je   40056f
   add  $0x1,%edi
   ```
   S2 & S1 != 0, so don't jump

Lecture Plan

- Recap: Assembly So Far
- Assembly Execution and %rip
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- **If statements**
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

If Statements

How can we use instructions like **cmp** and *conditional jumps* to implement if statements in assembly?

Practice: Fill In The Blank

```
int if_then(int param1) {
  if ( __________ ) {
     _________;
  }

  return __________;
}
```

```
0000000000401126 <if_then>:
  401126:   cmp    $0x6,%edi
  401129:   je     40112f
  40112b:   lea    (%rdi,%rdi,1),%eax
  40112e:   retq
  40112f:   add    $0x1,%edi
  401132:   jmp    40112b
```

Practice: Fill In The Blank

```c
int if_then(int param1) {
  if ( param1 == 6 ) {
       param1++;
  }

  return param1 * 2;
}
```

```
0000000000401126 <if_then>:
  401126:    cmp    $0x6,%edi
  401129:    je     40112f
  40112b:    lea    (%rdi,%rdi,1),%eax
  40112e:    retq
  40112f:    add    $0x1,%edi
  401132:    jmp    40112b
```

Common If-Else Construction

If-Else In C

```
long absdiff(long x, long y) {
    long result;
    if (x < y) {
        result = y - x;
    } else {
        result = x - y;
    }

    return result;
}
```

If-Else In Assembly pseudocode

```
Check opposite of code condition
Jump to else-body if test passes
If-body
Jump to past else-body
Else-body
Past else body
```

Practice: Fill in the Blank

If-Else In C

```
long absdiff(long x, long y) {
    long result;
    if (________) {

        ________________ ;
    } else {

        ________________ ;
    }

    return result;
}
```

```
401134 <+0>:   mov    %rsi,%rax
401137 <+3>:   cmp    %rsi,%rdi
40113a <+6>:   jge    0x401140 <absdiff+12>
40113c <+8>:   sub    %rdi,%rax
40113f <+11>:  retq
401140 <+12>:  sub    %rsi,%rdi
401143 <+15>:  mov    %rdi,%rax
401146 <+18>:  retq
```

If-Else In Assembly pseudocode

```
Check opposite of code condition
Jump to else-body if test passes
If-body
Jump to past else-body
Else-body
Past else body
```

Practice: Fill in the Blank

If-Else In C

```
long absdiff(long x, long y) {
    long result;
    if (_x < y_) {

        result = y - x ;
    } else {

        result = x - y ;
    }

    return result;
}
```

```
401134 <+0>:   mov    %rsi,%rax
401137 <+3>:   cmp    %rsi,%rdi
40113a <+6>:   jge    0x401140 <absdiff+12>
40113c <+8>:   sub    %rdi,%rax
40113f <+11>:  retq
401140 <+12>:  sub    %rsi,%rdi
401143 <+15>:  mov    %rdi,%rax
401146 <+18>:  retq
```

If-Else In Assembly pseudocode

```
Check opposite of code condition
Jump to else-body if test passes
If-body
Jump to past else-body
Else-body
Past else body
```

If-Else Construction Variations

C Code

```
int test(int arg) {
    int ret;
    if (arg > 3) {
        ret = 10;
    } else {
        ret = 0;
    }

    ret++;
    return ret;
}
```

Assembly

```
401134 <+0>:   cmp    $0x3,%edi
401137 <+3>:   jle    0x401142 <test+14>
401139 <+5>:   mov    $0xa,%eax
40113e <+10>:  add    $0x1,%eax
401141 <+13>:  retq
401142 <+14>:  mov    $0x0,%eax
401147 <+19>:  jmp    0x40113e <test+10>
```

Lecture Plan

- Recap: Assembly So Far
- Assembly Execution and %rip
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- **Loops**
  - **While loops**
  - For loops
- Other Instructions That Depend On Condition Codes

Loops and Control Flow

```c
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:     mov    $0x0,%eax
0x0000000000401161 <+5>:     cmp    $0x63,%eax
0x0000000000401164 <+8>:     jg     0x40116b <loop+15>
0x0000000000401166 <+10>:    add    $0x1,%eax
0x0000000000401169 <+13>:    jmp    0x401161 <loop+5>
0x000000000040116b <+15>:    retq
```

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Set %eax (i) to 0.

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:     mov    $0x0,%eax
0x0000000000401161 <+5>:     cmp    $0x63,%eax
0x0000000000401164 <+8>:     jg     0x40116b <loop+15>
0x0000000000401166 <+10>:    add    $0x1,%eax
0x0000000000401169 <+13>:    jmp    0x401161 <loop+5>
0x000000000040116b <+15>:    retq
```

Compare %eax (i) to 0x63 (99) by calculating %eax – 0x63. This is 0 – 99 = -99, so it sets the Sign Flag to 1.

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

jg means “jump if greater than”. This jumps if %eax > 0x63. The flags indicate this is false, so we do not jump.

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:     mov    $0x0,%eax
0x0000000000401161 <+5>:     cmp    $0x63,%eax
0x0000000000401164 <+8>:     jg     0x40116b <loop+15>
0x0000000000401166 <+10>:    add    $0x1,%eax
0x0000000000401169 <+13>:    jmp    0x401161 <loop+5>
0x000000000040116b <+15>:    retq
```

Add 1 to %eax (i).

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:     mov    $0x0,%eax
0x0000000000401161 <+5>:     cmp    $0x63,%eax
0x0000000000401164 <+8>:     jg     0x40116b <loop+15>
0x0000000000401166 <+10>:    add    $0x1,%eax
0x0000000000401169 <+13>:    jmp    0x401161 <loop+5>
0x000000000040116b <+15>:    retq
```

Jump to another instruction.

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

Compare %eax (i) to 0x63 (99) by calculating %eax – 0x63. This is 1 – 99 = -98, so it sets the Sign Flag to 1.

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

We continue in this pattern until we make this conditional jump. When will that be?

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:     mov    $0x0,%eax
0x0000000000401161 <+5>:     cmp    $0x63,%eax
0x0000000000401164 <+8>:     jg     0x40116b <loop+15>
0x0000000000401166 <+10>:    add    $0x1,%eax
0x0000000000401169 <+13>:    jmp    0x401161 <loop+5>
0x000000000040116b <+15>:    retq
```

We will stop looping when this comparison says that %eax > 0x63!

Loops and Control Flow

```
void loop() {
    int i = 0;
    while (i < 100) {
        i++;
    }
}
```

```
0x000000000040115c <+0>:     mov    $0x0,%eax
0x0000000000401161 <+5>:     cmp    $0x63,%eax
0x0000000000401164 <+8>:     jg     0x40116b <loop+15>
0x0000000000401166 <+10>:    add    $0x1,%eax
0x0000000000401169 <+13>:    jmp    0x401161 <loop+5>
0x000000000040116b <+15>:    retq
```

Then, we return from the function.

GCC Common While Loop Construction

C

```
while (test) {
      body
}
```

Assembly

```
Check opposite of code condition
Skip loop if test passes
Body
Jump back to test
```

From Previous Slide:

```
0x000000000040115c <+0>:    mov    $0x0,%eax
0x0000000000401161 <+5>:    cmp    $0x63,%eax
0x0000000000401164 <+8>:    jg     0x40116b <loop+15>
0x0000000000401166 <+10>:   add    $0x1,%eax
0x0000000000401169 <+13>:   jmp    0x401161 <loop+5>
0x000000000040116b <+15>:   retq
```

GCC Other While Loop Construction

C

```
while (test) {
      body
}
```

Assembly

```
Jump to check
Body
Check code condition
Jump to body if test passes
```

From Previous Slide:

```
0x0000000000400570 <+0>:     mov    $0x0,%eax
0x0000000000400575 <+5>:     jmp    0x40057a <loop+10>
0x0000000000400577 <+7>:     add    $0x1,%eax
0x000000000040057a <+10>:    cmp    $0x63,%eax
0x000000000040057d <+13>:    jle    0x400577 <loop+7>
0x000000000040057f <+15>:    repz retq
```

Lecture Plan

- Recap: Assembly So Far
- Assembly Execution and %rip
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- **Loops**
  - While loops
  - **For loops**
- Other Instructions That Depend On Condition Codes

Common For Loop Construction

C For loop

```
for (init; test; update) {
      body
}
```

C Equivalent While Loop

```
init
while(test) {
    body
    update
}
```

Assembly pseudocode

```
Init
Check opposite of code condition
Skip loop if test passes
Body
Update
Jump back to test
```

For loops and while loops are treated (essentially) the same when compiled down to assembly.

Back to Our First Assembly

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

```
0000000000401136 <sum_array>:
  401136 <+0>:   mov    $0x0,%eax
  40113b <+5>:   mov    $0x0,%edx
  401140 <+10>:  cmp    %esi,%eax
  401142 <+12>:  jge    0x40114f <sum_array+25>
  401144 <+14>:  movslq %eax,%rcx
  401147 <+17>:  add    (%rdi,%rcx,4),%edx
  40114a <+20>:  add    $0x1,%eax
  40114d <+23>:  jmp    0x401140 <sum_array+10>
  40114f <+25>:  mov    %edx,%eax
  401151 <+27>:  retq
```

1. Which register is C code's `sum`?
2. Which register is C code's `i`?
3. Which assembly instruction is C code's `sum += arr[i]`?
4. What are the **`cmp`** and **`jge`** instructions doing?
   (**`jge`**: signed jump greater than/equal)

Demo: GDB and Assembly

`sum_array.c`

gdb tips

`layout split` (ctrl-x a: exit, ctrl-l: resize)	View C, assembly, and gdb (lab5)
`info reg`	Print all registers
`p $eax`	Print register value
`p $eflags`	Print all condition codes currently set
`b *0x400546`	Set breakpoint at assembly instruction
`b *0x400550 if $eax > 98`	Set **conditional breakpoint**
`ni`	Next assembly instruction
`si`	Step into assembly instruction (will step into function calls)

gdb tips

`p/x $rdi`	Print register value in hex
`p/t $rsi`	Print register value in binary
`x $rdi`	Examine the byte stored at this address
`x/4bx $rdi`	Examine 4 bytes starting at this address
`x/4wx $rdi`	Examine 4 ints starting at this address

Lecture Plan

- Recap: Assembly So Far
- Assembly Execution and %rip
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- Loops
  - While loops
  - For loops
- **Other Instructions That Depend On Condition Codes**

Condition Code-Dependent Instructions

There are three common instruction types that use condition codes:

- **jmp** instructions conditionally jump to a different next instruction
- **set** instructions conditionally set a byte to 0 or 1
- new versions of **mov** instructions conditionally move data

set: Read condition codes

set instructions conditionally set a byte to 0 or 1.

- Reads current state of flags
- Destination is a single-byte register (e.g., %al) or single-byte memory location
- Does not perturb other bytes of register
- Typically followed by movzbl to zero those bytes

```
int small(int x) {
    return x < 16;
}
```

```
cmp $0xf,%edi
setle %al
movzbl %al, %eax
retq
```

`set`: Read condition codes

Instruction	Synonym	Set Condition (1 if true, 0 if false)
`sete D`	`setz`	Equal / zero
`setne D`	`setnz`	Not equal / not zero
`sets D`		Negative
`setns D`		Nonnegative
`setg D`	`setnle`	Greater (signed >)
`setge D`	`setnl`	Greater or equal (signed >=)
`setl D`	`setnge`	Less (signed <)
`setle D`	`setng`	Less or equal (signed <=)
`seta D`	`setnbe`	Above (unsigned >)
`setae D`	`setnb`	Above or equal (unsigned >=)
`setb D`	`setnae`	Below (unsigned <)
`setbe D`	`setna`	Below or equal (unsigned <=)

`cmov`: Conditional move

`cmovx src,dst` conditionally moves data in `src` to data in `dst`.

- Mov `src` to `dst` if condition x holds; no change otherwise
- `src` is memory address/register, `dst` is register
- May be more efficient than branch (i.e., jump)
- Often seen with C ternary operator: `result = test ? then: else;`

```
int max(int x, int y) {
    return x > y ? x : y;
}
```

```
cmp     %edi,%esi
mov     %edi, %eax
cmovge  %esi, %eax
retq
```

`cmov`: Conditional move

Instruction	Synonym	Move Condition
`cmove S,R`	`cmovz`	Equal / zero (ZF = 1)
`cmovne S,R`	`cmovnz`	Not equal / not zero (ZF = 0)
`cmovs S,R`		Negative (SF = 1)
`cmovns S,R`		Nonnegative (SF = 0)
`cmovg S,R`	`cmovnle`	Greater (signed >) (SF = 0 and SF = OF)
`cmovge S,R`	`cmovnl`	Greater or equal (signed >=) (SF = OF)
`cmovl S,R`	`cmovnge`	Less (signed <) (SF != OF)
`cmovle S,R`	`cmovng`	Less or equal (signed <=) (ZF = 1 or SF! = OF)
`cmova S,R`	`cmovnbe`	Above (unsigned >) (CF = 0 and ZF = 0)
`cmovae S,R`	`cmovnb`	Above or equal (unsigned >=) (CF = 0)
`cmovb S,R`	`cmovnae`	Below (unsigned <) (CF = 1)
`cmovbe S,R`	`cmovna`	Below or equal (unsigned <=) (CF = 1 or ZF = 1)

Last Lab: Conditional Move

```
int signed_division(int x) {
     return x / 4;
}
```

```
signed_division:
  leal 3(%rdi), %eax        Put x + 3 into %eax
  testl %edi, %edi          Check the sign of x
  cmovns %edi, %eax         If x is positive, put x into %eax
  sarl $2, %eax             Divide %eax by 4
  ret
```

Optimizations

- **Conditional Moves** can sometimes eliminate "branches" (jumps), which are particularly inefficient on modern computer hardware.
- Processors try to *predict* the future execution of instructions for maximum performance. This is difficult to do with jumps.
- This is called **branch prediction** / **speculative execution**
- The **Spectre** vulnerability exploited an issue with this on modern processors to access protected information
- Processors may also use *out-of-order execution* (look ahead)
- The **Meltdown** vulnerability exploited an issue with out-of-order execution on modern processors to access protected data
- https://meltdownattack.com

Recap

- Recap: Assembly So Far
- Assembly Execution and %rip
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements
- Loops
  - While loops
  - For loops
- Other Instructions That Depend On Condition Codes

Lecture 12 takeaway: We represent control flow in assembly by storing information in condition codes and having instructions that act differently depending on the condition code values. Loops and conditionals commonly use cmp or test along with jumps to conditionally skip over or repeat assembly instructions.

Next time: Function calls in assembly

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = ___(1)___;
    while (___(2)___) {
      result = ____(3)_____;
      a = ___(4)___;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax
<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>
<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi
<+22>:  jmp    0x113e <loop+5>
<+24>:  retq
```

GCC common while loop construction:

Test
Jump past loop if fails
Body
Jump to test

https://godbolt.org/z/zrW6c5MGa

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = ___(1)___;
    while (___(2)___) {
      result = ____(3)_____;
      a = ___(4)___;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax
<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>
<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi
<+22>:  jmp    0x113e <loop+5>
<+24>:  retq
```

GCC common while loop construction:

Test
Jump past loop if fails
Body
Jump to test

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = _________;
    while (_________) {
      result = ____________;
      a = _________;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax

<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>

<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi

<+22>:  jmp    0x113e <loop+5>

<+24>:  retq
```

Practice: Fill in the blanks

```
long loop(long a, long b) {
    long result = ____1____;
    while (__a < b__) {
      result = result*(a+b);
      a = __a + 1__;
    }
    return result;
}
```

```
<+0>:   mov    $0x1,%eax

<+5>:   cmp    %rsi,%rdi
<+8>:   jge    0x1151 <loop+24>

<+10>:  lea    (%rdi,%rsi,1),%rdx
<+14>:  imul   %rdx,%rax
<+18>:  add    $0x1,%rdi

<+22>:  jmp    0x113e <loop+5>

<+24>:  retq
```

`test` practice: What’s the C code?

```
0x400546 <test_func>     test   %edi,%edi
0x400548 <test_func+2>   jns    0x400550 <test_func+10>
0x40054a <test_func+4>   mov    $0xfeed,%eax
0x40054f <test_func+9>   retq
0x400550 <test_func+10>  mov    $0xaabbccdd,%eax
0x400555 <test_func+15>  retq
```

test practice: What's the C code?

```
0x400546 <test_func>     test   %edi,%edi
0x400548 <test_func+2>   jns    0x400550 <test_func+10>
0x40054a <test_func+4>   mov    $0xfeed,%eax
0x40054f <test_func+9>   retq
0x400550 <test_func+10>  mov    $0xaabbccdd,%eax
0x400555 <test_func+15>  retq
```

```
int test_func(int x) {
    if (x < 0) {
        return 0xfeed;
    }
    return 0xaabbccdd;
}
```

(or anything like this)

Practice: “Escape Room”

```
<escape_room+0>     lea    (%rdi,%rdi,1),%eax
<escape_room+3>     cmp    $0x5,%eax
<escape_room+6>     jg     0x114c <escape_room+19>
<escape_room+8>     cmp    $0x1,%edi
<escape_room+11>    je     0x1152 <escape_room+25>
<escape_room+13>    mov    $0x0,%eax
<escape_room+18>    retq
<escape_room+19>    mov    $0x1,%eax
<escape_room+24>    retq
<escape_room+25>    mov    $0x1,%eax
<escape_room+30>    retq
```

What must be passed to the escapeRoom function such that it returns true (1) and not false (0)?

You don’t have to reverse-engineer C code exactly!
Just figure out the big picture!

Practice: “Escape Room”

```
<escape_room+0>     lea    (%rdi,%rdi,1),%eax
<escape_room+3>     cmp    $0x5,%eax
<escape_room+6>     jg     0x114c <escape_room+19>
<escape_room+8>     cmp    $0x1,%edi
<escape_room+11>    je     0x1152 <escape_room+25>
<escape_room+13>    mov    $0x0,%eax
<escape_room+18>    retq
<escape_room+19>    mov    $0x1,%eax
<escape_room+24>    retq
<escape_room+25>    mov    $0x1,%eax
<escape_room+30>    retq
```

What must be passed to the escapeRoom function such that it returns true (1) and not false (0)?

First param > 2 or == 1.

Exercise 2: Conditional jump

```
00000000004004d6 <if_then>:
  4004d6:   83 ff 06    cmp    $0x6,%edi
  4004d9:   75 03       jne    4004de <if_then+0x8>
  400rdb:   83 c7 01    add    $0x1,%edi
  4004de:   8d 04 3f    lea    (%rdi,%rdi,1),%eax
  4004e1:   c3          retq
```

%edi `0x5`

1. What is the value of `%rip` after executing the `jne` instruction?
   A. `4004d9`
   B. `4004db`
   C. `4004de`
   D. Other

2. What is the value of `%eax` when we hit the `retq` instruction?
   A. `4004e1`
   B. `0x2`
   C. `0xa`
   D. `0xc`
   E. Other

🤔

Exercise 2: Conditional jump

```
0000000004004d6 <if_then>:
  4004d6:   83 ff 06    cmp    $0x6,%edi
  4004d9:   75 03       jne    4004de <if_then+0x8>
  400rdb:   83 c7 01    add    $0x1,%edi
  4004de:   8d 04 3f    lea    (%rdi,%rdi,1),%eax
  4004e1:   c3          retq
```

%edi `0x5`

1. What is the value of `%rip` after executing the `jne` instruction?
   A. 4004d9
   B. 4004db
   C. 4004de
   D. Other

2. What is the value of `%eax` when we hit the `retq` instruction?
   A. 4004e1
   B. 0x2
   C. 0xa
   D. 0xc
   E. Other