COMP201

Computer Systems & Programming

Lecture #22 – Control Flow

KOÇ UNIVERSITY

Aykut Erdem // Koç University // Fall 2020

Good news, everyone!

- Assignment 4 will be out on Nov 27 (due Dec 11)
- Midterm exam will be held on December 5, 2020 (Saturday) at 11:45am
  - More info on Friday

Learning Assembly

Moving data around	Arithmetic and logical operations	Control flow	Function calls
Lecture 19	Lecture20	This week	Lecture 24-26

Learning Goals

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

Plan for Today

- Assembly Execution and `%rip` (cont'd.)
- Control Flow Mechanics
- If statements

Disclaimer: Slides for this lecture were borrowed from

—Nick Troccoli's Stanford CS107 class

Lecture Plan

- Assembly Execution and `%rip` (cont'd.)
- Control Flow Mechanics
- If statements

Recap: 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

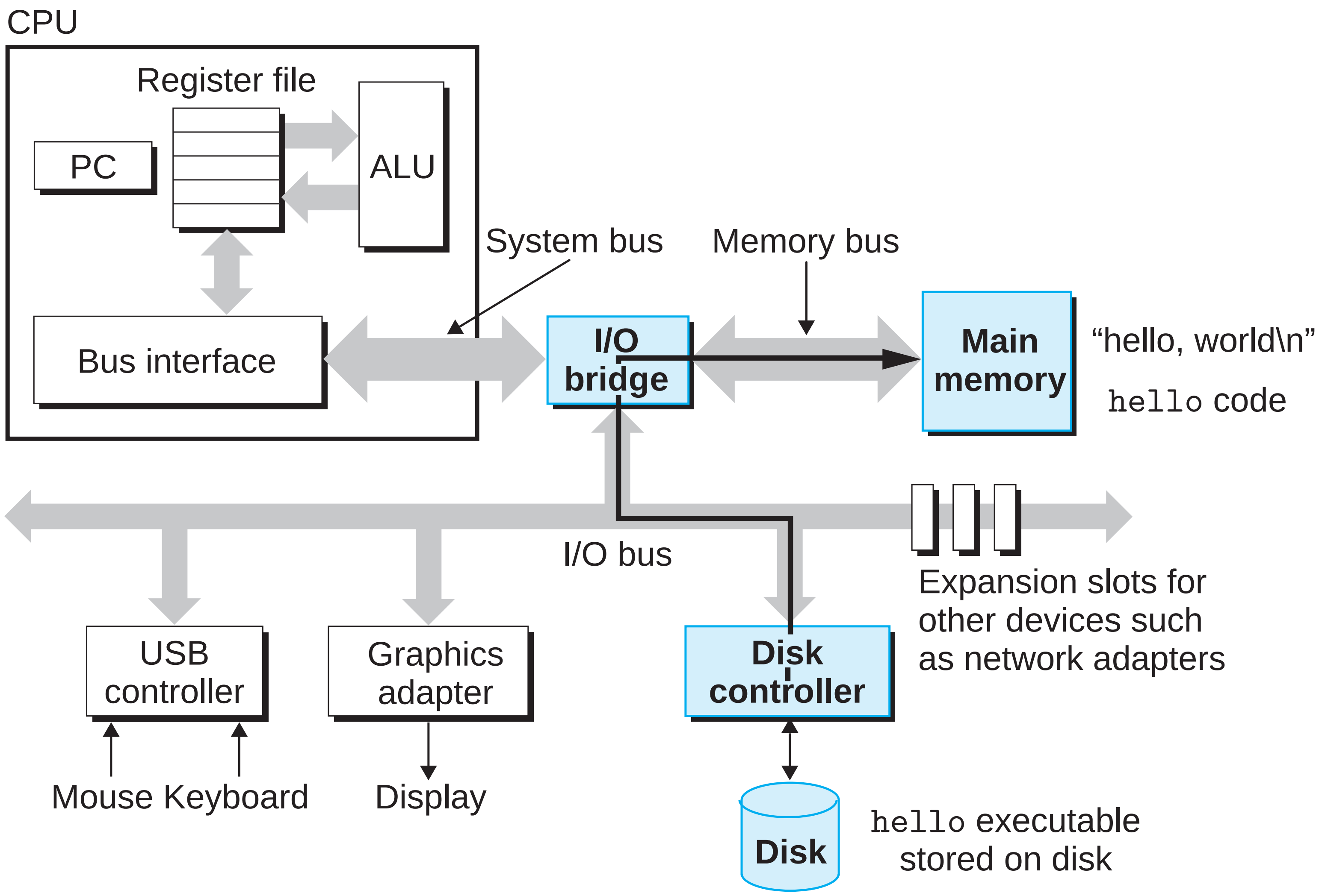
Register Responsibilities

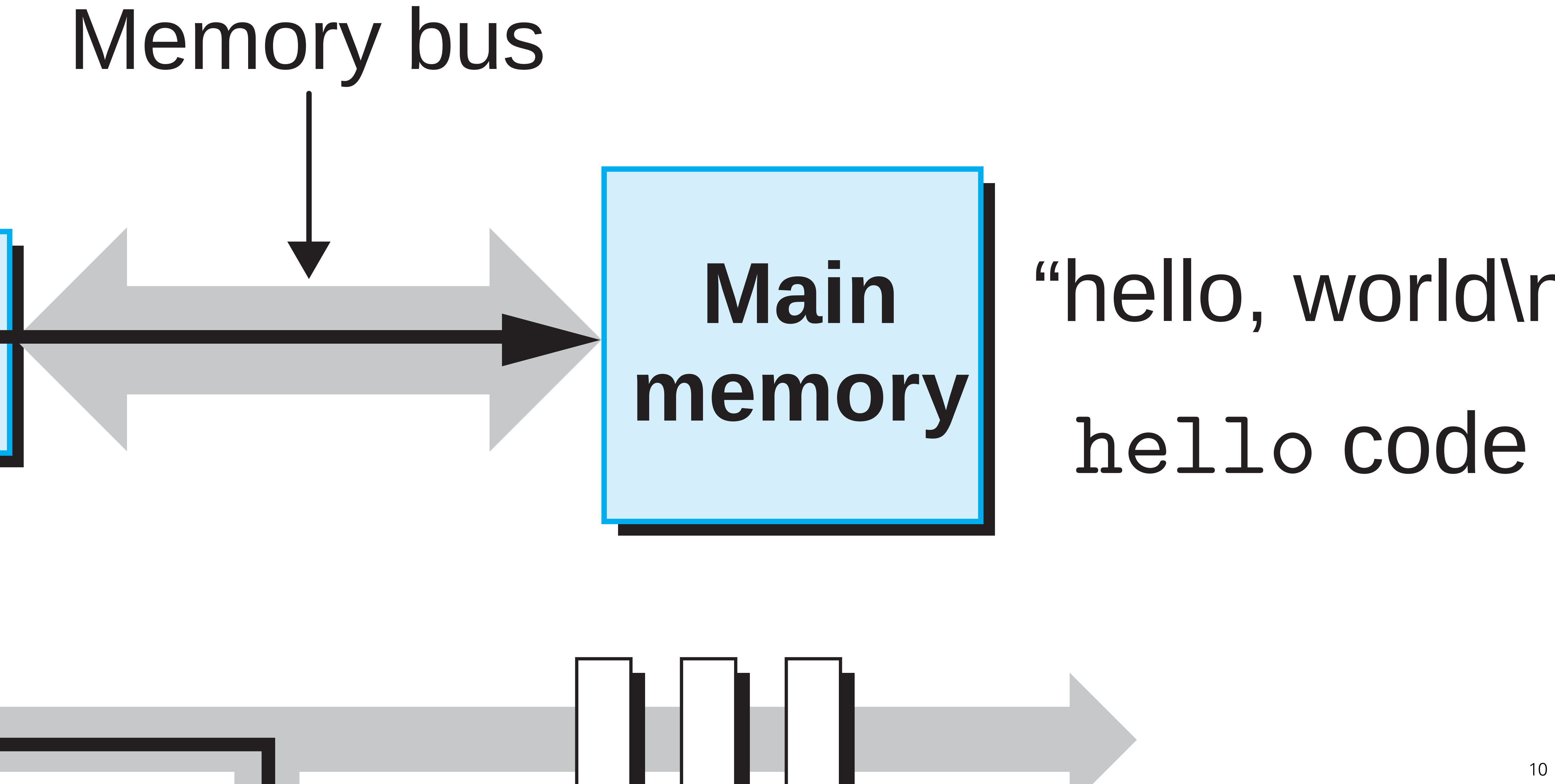
Some registers take on special responsibilities during program execution.

- **`%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!

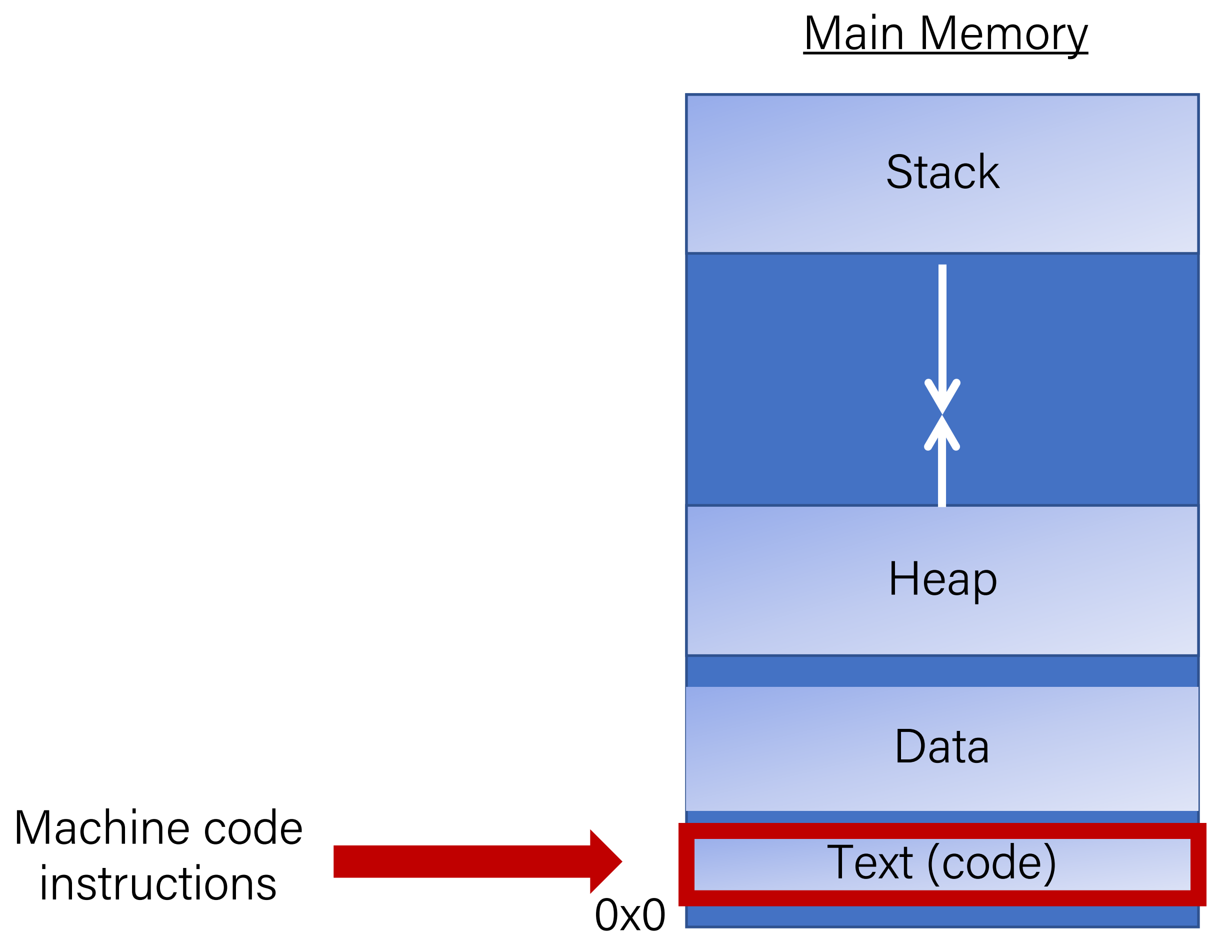
Instructions Are Just Bytes!





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

Instructions Are Just Bytes!



%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
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4004ee	48
4004ed	55

%rip

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4004f1: c7 45 fc 00 00 00 00    movl   $0x0,-0x4(%rbp)
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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.

`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
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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

```
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
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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.

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>
```

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
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4004fa	fc
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4004f6	00
4004f5	00
4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

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>
```

4004fd	fa
4004fc	eb
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4004f5	00
4004f4	00
4004f3	fc
4004f2	45
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4004f0	e5
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4004ed	55

Special hardware sets the program counter to the next instruction:

`%rip` += size of bytes of current instruction

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>
```

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

```
0x4004fc
```

%rip

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
4004f3	fc
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Jump!

```
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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)
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4004fc	eb
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4004f4	00
4004f3	fc
4004f2	45
4004f1	c7
4004f0	e5
4004ef	89
4004ee	48
4004ed	55

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)
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4004fd	fa
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4004fb	01
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4004f9	45
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4004ef	89
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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) {…}
```

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

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

- Assembly Execution and `%rip` (cont'd.)
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements

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

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

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

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 %ed
cmp $3, %edi
jne [target]
```

```
// Jump if %edi <= 1
%edi
get]
```

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.

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.

Example: if we calculate t = a + b, condition codes are set according to:

- **CF**: Carry flag (Unsigned Overflow). `(unsigned) t < (unsigned) a`
- **ZF**: Zero flag (Zero). `(t == 0)`
- **SF**: Sign flag (Negative). `(t < 0)`
- **OF**: Overflow flag (Signed Overflow). `(a<0 == b<0) && (t<0 != a<0)`

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]
```

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!

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

Exercise 2: Conditional jump

slido Event code: 73165

```
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

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

slido Event code: 73165

```
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

Exercise 2: Conditional jump

slido Event code: 73165

```
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

Lecture Plan

- Assembly Execution and `%rip` (cont'd.)
- Control Flow Mechanics
- If statements

If Statements

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

Practice: Fill In The Blank

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

  return __________;
}
```

```
00000000004004d6 <if_then>:
  4004d6:    cmp  $0x6,%edi
  4004d9:    jne  4004de
  4004db:    add  $0x1,%edi
  4004de:    lea  (%rdi,%rdi,1),%eax
  4004e1:    retq
```

Practice: Fill In The Blank

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

  return  param1 * 2;
}
```

```
0000000000004004d6 <if_then>:
  4004d6:    cmp   $0x6,%edi
  4004d9:    jne   4004de
  4004db:    add   $0x1,%edi
  4004de:    lea   (%rdi,%rdi,1),%eax
  4004e1:    retq
```

Practice: Fill In The Blank

If-Else In C

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

ret++;
```

If-Else In Assembly pseudocode

```
Test
Jump to else-body if test fails
If-body
Jump to past else-body
Else-body
Past else body
```

Practice: Fill In The Blank

If-Else In C

```
if ( __________ ) {
     _________;
} else {
     ________;
}
______;
```

```
400552 <+0>:   cmp   $0x3,%edi
400555 <+3>:   jle   0x40055e <if_else+12>
400557 <+5>:   mov   $0xa,%eax
40055c <+10>:  jmp   0x400563 <if_else+17>
40055e <+12>:  mov   $0x0,%eax
400563 <+17>:  add   $0x1,%eax
```

If-Else In Assembly pseudocode

```
Test
Jump to else-body if test fails
If-body
Jump to past else-body
Else-body
Past else body
```

Practice: Fill In The Blank

If-Else In C

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

```
400552 <+0>:  cmp   $0x3,%edi
400555 <+3>:  jle   0x40055e <if_else+12>
400557 <+5>:  mov   $0xa,%eax
40055c <+10>: jmp   0x400563 <if_else+17>
40055e <+12>: mov   $0x0,%eax
400563 <+17>: add   $0x1,%eax
```

If-Else In Assembly pseudocode

```
Test
Jump to else-body if test fails
If-body
Jump to past else-body
Else-body
Past else body
```

Recap

- Assembly Execution and `%rip` (cont'd.)
- Control Flow Mechanics
  - Condition Codes
  - Assembly Instructions
- If statements

Next time: Loops, other instructions that depend on condition codes