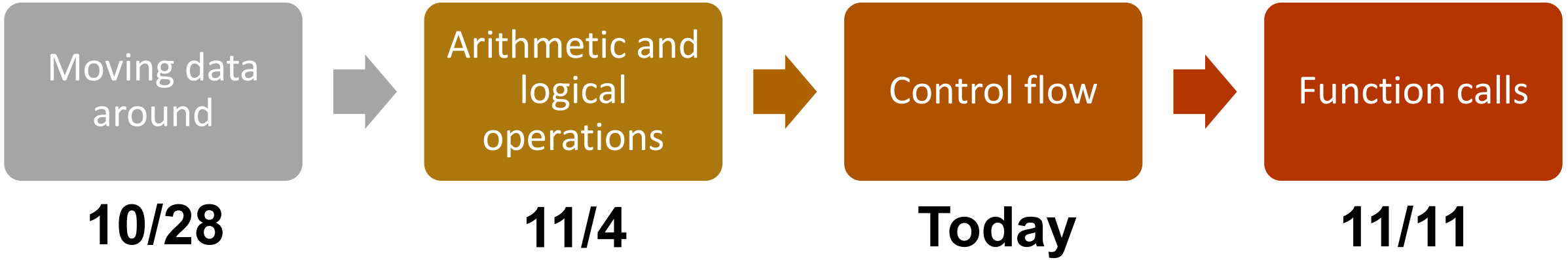
CS107, Lecture 13
Assembly: Control Flow

Reading: B&O 3.6

Learning Assembly



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

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

- Recap: Arithmetic and Logic
- Control Flow
  - Condition Codes
  - Assembly Instructions
  - If statements
  - While loops
  - For loops

Plan For Today

- **Recap: Arithmetic and Logic**
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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!

mov Variants

- **mov** can take an optional suffix (b,w,l,q) that specifies the size of data to move: `movb, movw, movl, movq`
- **mov** only updates the specific register bytes or memory locations indicated.
  - **Exception: movl** writing to a register will also set high order 4 bytes to 0.

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.

No-Op

- The **nop/nopl** instructions are “no-op” instructions – they do nothing!
- Why? To make functions align on nice multiple-of-8 address boundaries.

> “Sometimes, doing nothing is the way to be most productive.” – Philosopher Nick

Mov

- Sometimes, you'll see the following: **mov %ebx, %ebx**
- What does this do? It zeros out the top 32 register bits, because when mov is performed on an e- register, the rest of the 64 bits are zeroed out.

xor

- Sometimes, you'll see the following: **xor %ebx, %ebx**
- What does this do? It sets %ebx to zero! May be more efficient than using **mov**.

Assembly Exercise 1

```
0000000004005ac <sum_example1>:
    4005bd:   8b 45 e8        mov  %esi,%eax
    4005c3:   01 d0           add  %edi,%eax
    4005cc:   c3              retq
```

Which of the following is most likely to have generated the above assembly?

```
// A)
void sum_example1() {
    int x;
    int y;
    int sum = x + y;
}
```

```
// B)
int sum_example1(int x, int y) {
    return x + y;
}
```

```
// C)
void sum_example1(int x, int y) {
    int sum = x + y;
}
```

Assembly Exercise 2

```
0000000000400578 <sum_example2>:
    400578:   8b 47 0c        mov  0xc(%rdi),%eax
    40057b:   03 07           add  (%rdi),%eax
    40057d:   2b 47 18        sub  0x18(%rdi),%eax
    400580:   c3              retq
```

```
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly above represents the C code's **sum** variable?

Assembly Exercise 2

```
0000000000400578 <sum_example2>:
    400578:   8b 47 0c        mov  0xc(%rdi),%eax
    40057b:   03 07           add  (%rdi),%eax
    40057d:   2b 47 18        sub  0x18(%rdi),%eax
    400580:   c3              retq
```

```
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly above represents the C code's **sum** variable?

%eax

Assembly Exercise 3

```
0000000000400578 <sum_example2>:
    400578:   8b 47 0c        mov  0xc(%rdi),%eax
    40057b:   03 07           add  (%rdi),%eax
    40057d:   2b 47 18        sub  0x18(%rdi),%eax
    400580:   c3              retq
```

```
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly code above represents the C code's **6** (as in **arr[6]**)?

Assembly Exercise 3

```
0000000000400578 <sum_example2>:
    400578:   8b 47 0c        mov  0xc(%rdi),%eax
    40057b:   03 07           add  (%rdi),%eax
    40057d:   2b 47 18        sub  0x18(%rdi),%eax
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```

```
int sum_example2(int arr[]) {
    int sum = 0;
    sum += arr[0];
    sum += arr[3];
    sum -= arr[6];
    return sum;
}
```

What location or value in the assembly code above represents the C code's **6** (as in **arr[6]**)?

0x18

Plan For Today

- Recap: Arithmetic and Logic
- **Control Flow**
  - Condition Codes
  - Assembly Instructions
  - If statements
  - While loops
  - For loops

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?
  - A way to store conditions that we will check later
  - Assembly instructions whose behavior is dependent on these conditions

Control

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

In Assembly:

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

There are special “condition code” registers that automatically store the results of the most recent arithmetic or logical operation.

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

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.

Which flag would be set after this code?

```
int a = 5;
int b = -5;
int t = a + b;
```

Condition Codes

Common Condition Codes

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Which flag would be set after this code?

```
int a = 5;
int b = -20;
int t = a + b;
```

Condition Codes

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.
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- **OF:** Overflow flag. The most recent operation caused a two's-complement overflow-either negative or positive.

Which flag would be set after this code?

```
int a = 5;
int b = -20;
int t = a + b;
```

Condition Codes

- Different combinations of condition codes can indicate different things.
  - E.g. To check equality, we can look at the ZERO flag (a = b means a – b = 0)
- 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.

Setting Condition Codes

In addition to being set automatically from logical and arithmetic operations, we can also update condition codes ourselves.

- 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

Setting Condition Codes

In addition to being set automatically from logical and arithmetic operations, we can also update condition codes ourselves.

- The **test** instruction is like the AND instruction, but 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!

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?
  - A way to store conditions that we will check later
  - **Assembly instructions whose behavior is dependent on these conditions**

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Condition Code-Dependent Instructions

There are three common instruction types that use condition codes:

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

Conditionally Setting Bytes

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 <=)

Conditionally Moving Data

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)

Conditionally Moving Data – Lab6

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

```
signed_division:
  leal 3(%rdi), %eax
  testl %edi, %edi
  cmovns %edi, %eax
  sarl $2, %eax
  ret
```

Put x + 3 into %eax

Check the sign of x

If x is positive, put x into %eax

Divide %eax by 4

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 read from a memory location (indirect jump):

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

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 (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 >) (SF = 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)

Loops and Control Flow

Jump instructions are critical to implementing control flow in assembly. Let's see why!

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Practice: Fill In The Blank

C Code

```
int if_then(int param1) {
    if (____________) {
        ____________;
    }

    return ______;
}
```

What does this assembly code translate to?

```
0000000004004d6 <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 Code

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

    return ______;
}
```

What does this assembly code translate to?

```
0000000004004d6 <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 Code

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

    return ______;
}
```

What does this assembly code translate to?

```
0000000004004d6 <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 Code

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

    return param1 * 2;
}
```

What does this assembly code translate to?

```
0000000004004d6 <if_then>:
  4004d6:   cmp    $0x6,%edi
  4004d9:   jne    4004de
  4004db:   add    $0x1,%edi
  4004de:   lea    (%rdi,%rdi,1),%eax
  4004e1:   retq
```

Common If-Else Construction

If-Else In C

```
if (num > 3) {
    x = 10;
} else {
    x = 7;
}

num++;
```

If-Else In Assembly

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

Announcements

- Mid-Quarter Check-in page posted on course website
- Midterm grade added to Gradebook page
- Note about makeup labs
- Assignment 6 released tomorrow – Assembly exercises
  - Security
  - Reverse engineering

Mid-Lecture Check-In

We can now answer the following questions:

1. How does assembly keep track of the result of the most recent arithmetic or logical operation?
2. What is the difference between **`cmp`** and **`sub?`** Between **`test`** and **`and`**?
3. Why is the **`jmp`** family of instructions crucial for implementing control flow?

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Loops and Control Flow

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

```
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
```

Loops and Control Flow

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

```
0x0000000000400570 <+0>:    mov    $0x0,%eax
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0x000000000040057d <+13>:   jle    0x400577 <loop+7>
0x000000000040057f <+15>:   repz retq
```

Set %eax (i) to 0.

Loops and Control Flow

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

```
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
```

Jump to another instruction.

Loops and Control Flow

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

```
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
```

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++;
    }
}
```

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

jle means “jump if less than or equal”. The sign flag indicates the result was negative, so we jump.

Loops and Control Flow

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

```
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
```

Add 1 to %eax (i).

Loops and Control Flow

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

```
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
```

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++;
    }
}
```

```
0x0000000000400570 <+0>:     mov    $0x0,%eax
0x0000000000400575 <+5>:     jmp    0x40057a <loop+10>
0x0000000000400577 <+7>:     add    $0x1,%eax
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```

jle means “jump if less than or equal”. The sign flag indicates the result was negative, so we jump.

Loops and Control Flow

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

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0x0000000000400570 <+0>:     mov    $0x0,%eax
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0x000000000040057f <+15>:    repz retq
```

We continue in this pattern until we do not make this conditional jump. When will that be?

Loops and Control Flow

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

```
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
```

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

Loops and Control Flow

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

```
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
```

Then, we return from the function.

Common While Loop Construction

C

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

Assembly

```
Jump to test
Body
Test
Jump to body if success
```

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
```

Plan For Today

- Recap: Arithmetic and Logic
- **Control Flow**
  - Condition Codes
  - Assembly Instructions
  - If statements
  - While loops
  - **For loops**

Common For Loop Construction

C

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

Common For Loop Construction

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

C Equivalent While Loop

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

Common For Loop Construction

C

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

C Equivalent While Loop

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

While Loop Assembly

```
Jump to test
Body
Test
Jump to body if success
```

Common For Loop Construction

C

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

C Equivalent While Loop

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

For Loop Assembly

```
Init
Jump to test
Body
```

```
Update
Test
Jump to body if success
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

```
for (int i = 0; i < n; i++)          // n = 100
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Jump to test
Test
Jump to body
Body
Update
Test
Jump to body
Body
Update
Test
Jump to body
...
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Jump to test
Test
Jump to body
Body
Update
Test
Jump to body
Body
Update
Test
Jump to body
...
```

GCC For Loop Output

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Test
No jump
Body
Update
Jump to test
Test
No jump
Body
Update
Jump to test
...
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

GCC For Loop Output

```
for (int i = 0; i < n; i++)          // n = 100

Initialization
Test
No jump
Body
Update
Jump to test
Test
No jump
Body
Update
Jump to test
...
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

GCC For Loop Output

GCC For Loop Output

```
Initialization
Jump to test
Body
Update
Test
Jump to body if success
```

Possible Alternative?

```
Initialization
Test
Jump past loop if fails
Body
Update
Jump to test
```

Which instructions are better when n = 0?

for (int i = 0; i < n; i++)

Optimizing Instruction Counts

- Both loop forms have the same **static instruction count** – same number of written instructions.
- But they have different **dynamic** instruction counts – the number of times these instructions are executed when the program is run.
  - If n = 0, right is best
  - If n is large, left is best
- The compiler may emit static instruction counts many times longer than alternatives, but which is more efficient if loop executes many times.
- Problem: the compiler may not know whether the loop will execute many times! Hard problem….. (take EE108, EE180, CS316 for more!)

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.

Practice: Fill In The Blank

C Code

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

Common while loop construction:

Jump to test
Body
Test
Jump to body if success

What does this assembly code translate to?

```
// a in %rdi, b in %rsi
loop:
    movl $1, %eax
    jmp .L2
.L3
    leaq (%rdi,%rsi), %rdx
    imulq %rdx, %rax
    addq $1, %rdi
.L2
    cmpq %rsi, %rdi
    jl .L3
rep; ret
```

Practice: Fill In The Blank

C Code

```
long loop(long a, long b) {
    long result = 1;
    while (__________) {
      result = ___________;
      a = __________;
    }
    return result;
}
```

Common while loop construction:

Jump to test
Body
Test
Jump to body if success

What does this assembly code translate to?

```
// a in %rdi, b in %rsi
loop:
    movl $1, %eax
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    addq $1, %rdi
.L2
    cmpq %rsi, %rdi
    jl .L3
rep; ret
```

Practice: Fill In The Blank

C Code

```
long loop(long a, long b) {
    long result = 1;
    while (a < b) {
      result = ____________;
      a = ____________;
    }
    return result;
}
```

Common while loop construction:

Jump to test
Body
Test
Jump to body if success

What does this assembly code translate to?

```
// a in %rdi, b in %rsi
loop:
    movl $1, %eax
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    imulq %rdx, %rax
    addq $1, %rdi
.L2
    cmpq %rsi, %rdi
    jl .L3
rep; ret
```

Practice: Fill In The Blank

C Code

```
long loop(long a, long b) {
    long result = 1;
    while (a < b) {
      result = result*(a+b);
      a = _____;
    }
    return result;
}
```

Common while loop construction:

Jump to test
Body
Test
Jump to body if success

What does this assembly code translate to?

```
// a in %rdi, b in %rsi
loop:
    movl $1, %eax
    jmp .L2
.L3
    leaq (%rdi,%rsi), %rdx
    imulq %rdx, %rax
    addq $1, %rdi
.L2
    cmpq %rsi, %rdi
    jl .L3
rep; ret
```

Practice: Fill In The Blank

C Code

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

Common while loop construction:

Jump to test
Body
Test
Jump to body if success

What does this assembly code translate to?

```
// a in %rdi, b in %rsi
loop:
    movl $1, %eax
    jmp .L2
.L3
    leaq (%rdi,%rsi), %rdx
    imulq %rdx, %rax
    addq $1, %rdi
.L2
    cmpq %rsi, %rdi
    jl .L3
rep; ret
```

Plan For Today

- Recap: Arithmetic and Logic
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  - If statements
  - While loops
  - For loops

Next time: function calls in assembly