CS107 Lecture 17
Assembly: Arithmetic and Logic Wrap, Control Flow

Reading: B&O 3.5-3.6

Multiplication Support

Multiplying 64-bit numbers can produce **128-bit results**. How does x86-64 support this with only 64-bit registers?

- If you specify **two operands** to **`imul`** or **`mul`**, it multiplies them and truncates the result to fit in the second of the two.

`imul S, D` is realized as `D ← D * S`

- If you specify one operand, it's multiplied by **`%rax`** and the product is split across **two** registers: the high-order 64 bits go in **`%rdx`** and the low-order 64 bits in `%rax`.

Instruction	Effect	Description
`imulq S`	`R[%rdx]:R[%rax] ← S x R[%rax]`	Signed full multiply
`mulq S`	`R[%rdx]:R[%rax] ← S x R[%rax]`	Unsigned full multiply

Division and Mod Support

`x86-64` supports **dividing a 128-bit value by a 64-bit value**.

Instruction	Effect	Description

`idivq S`	`R[%rdx] ← R[%rdx]:R[%rax] mod S;`
	`R[%rax] ← R[%rdx]:R[%rax] ÷ S`
		Signed divide

`divq S`	`R[%rdx] ← R[%rdx]:R[%rax] mod S;`
	`R[%rax] ← R[%rdx]:R[%rax] ÷ S`
		Unsigned divide

`cqto`	`R[%rdx]:R[%rax] ← SignExtend(R[%rax])`	Convert to oct word

- The **high-order 64 bits of the dividend** need to be prepared and stored in **`%rdx`**, the **low-order 64 bits** in **`%rax`**. The divisor is the only listed operand.
- The **integer quotient** is stored in **`%rax`**, and the **remainder** in **`%rdx`**.
- Most dividend are just 64-bit. The **`cqto`** instruction **sign-extends the 64-bit** value in **`%rax`** though **`%rdx`** to fill **both registers with the dividend**, as **`idiv`** and **`div`** expect.

Reverse Engineering Etude

Examine the **assembly code** emitted on behalf of the three-argument **`div_and_mod`** function and **reconstruct an equivalent, four-line implementation** in C.

Assembly:

```
div_and_mod:
   movq %rdi, %rax
   movq %rdx, %rcx
   cqto
   idivq %rsi
   movq %rdx, (%rcx)
   ret
```

C:

```
long div_and_mod(long x, long y, long *p_mod) {
   long quotient = x / y;
   long remainder = x % y;
   *p_mod = remainder;
   return quotient;
}
```

Key Insights:

- The **first and third lines of assembly** suggest **`x`**—delivered via **`%rdi`**—is the **dividend** of the forthcoming division.
- The **second line** stores a copy of **`p_mod`** (courtesy of **`%rdx`**) in **`%rcx`**.
- The **fourth line** divides **`x`** by **`y`** (supplied via **`%rsi`**), populating **`%rax`** with the **integer quotient** and **`%rdx`** with the **remainder**.
  - This explains why a **copy** of **`p_mod`** was placed in **`%rcx`**—the **compiler recognized** **`%rdx`** would be **overwritten** by **`idivq`** two lines later.
- The **remainder is written through the address stored in `%rcx`**, suggesting **`*p_mod = x % y`**
- **`%rax`** still holds **the integer quotient when the function returns**, suggesting something akin to **`return x / y`**

Reverse Engineering Etude 1

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- **`%rax`** still holds **the integer quotient when the function returns**, suggesting something akin to **`return x / y`**

Reverse Engineering Etude

Examine the **assembly code** emitted on behalf of the three-argument **`tinker_toy`** function and **complete the implementation**.

Assembly:

```
tinker_toy:
    movslq %edx, %rdx
    movl %edi, %eax
    addl (%rsi,%rdx,4), %eax
    ret
```

C:

```
int tinker_toy(int x, int arr[], int y) {
    int sum = _____x_____;
    sum += arr[_____y_____];
    return ____sum____;
}
```

Key Insights:

- Because the third argument **y** is an **`int`**, it's really passed in **`%edx`**, and the **upper half** of **`%rdx`** is **irrelevant garbage**.
- However, a **sign-extended copy** of **y** is placed in **`%rdx`** via the first instruction, since the **addressing mode of the third line requires full registers**. **`%edx`** itself doesn't qualify.
- Because **`sum`** is declared as an **`int`** and is the **focus of the implementation**, it's reasonable to assume **`sum`** is backed by **`%eax`** and that its **final value is what's returned**.
- The second line **initializes** **`sum`** to **`x`**, and the third **adds** **`arr[y]`** to **`sum`**. Note the **scale factor** in line three is a 4, and that's what you'd expect with **`int *`** pointer arithmetic.

Executing Instructions

So far:

- Program values **can be stored in memory or in registers**.
- Assembly instructions **read and write values** back and forth between **registers and main memory**.
- Assembly instructions are **also stored in memory**.

Big Questions:

- **What controls execution flow**? How does a process know what instruction to **execute next**?

Answer:

- The **program counter**, stored in `%rip`.

4004fd	fa
4004fc	eb
4004fb	01
4004fa	fc
4004f9	45
4004f8	83
4004f7	00
4004f6	00
4004f5	00
4004f4	00
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4004ee	48
4004ed	55

Followin

```
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>
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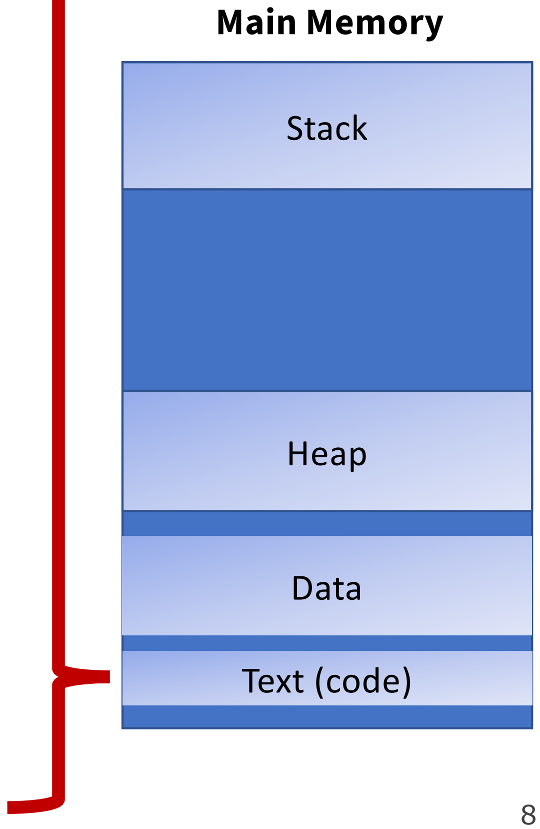

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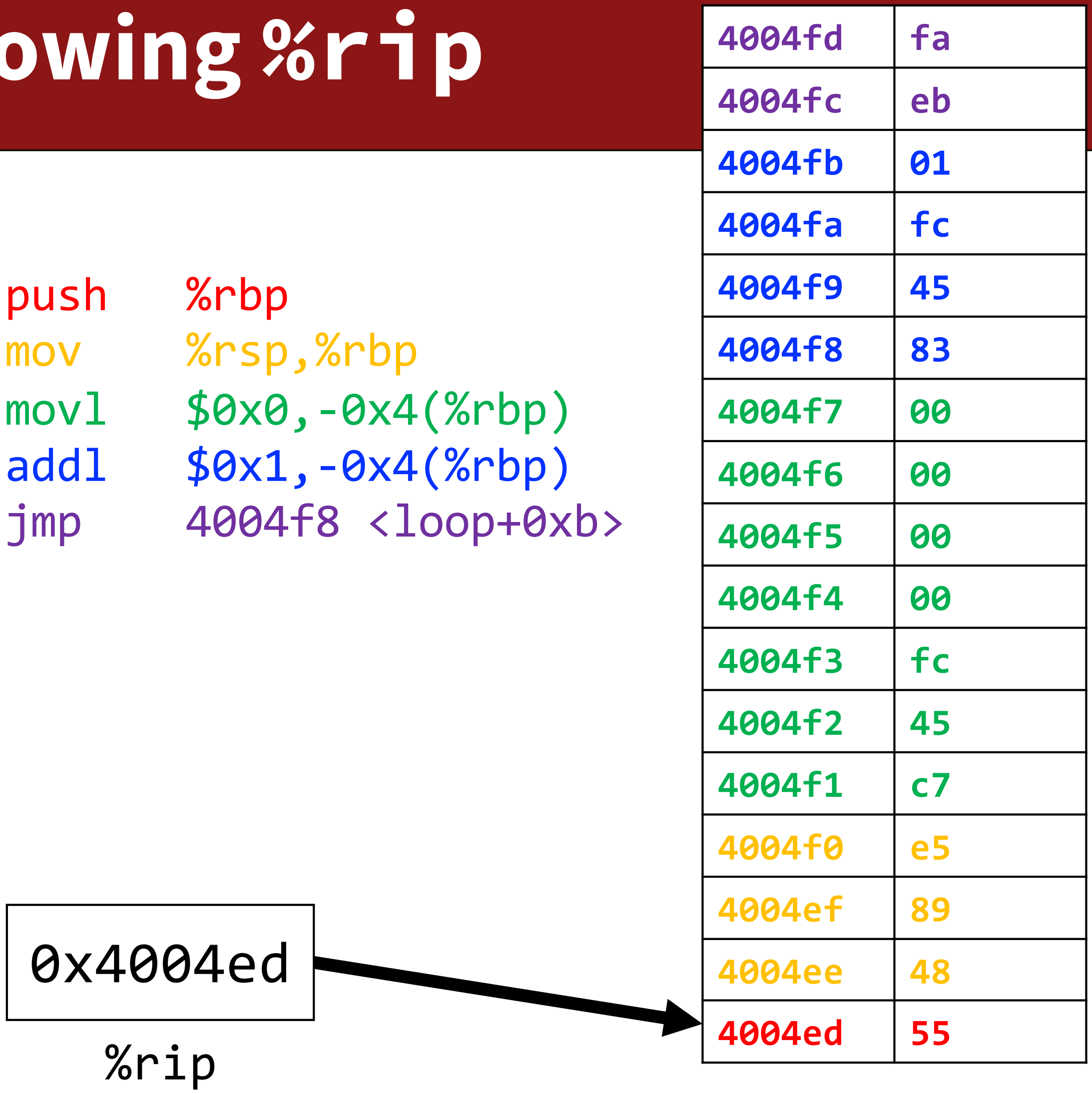
In x86-64, **`%rip`** serves as the **program counter** and holds the address of the **next instruction to be executed**.



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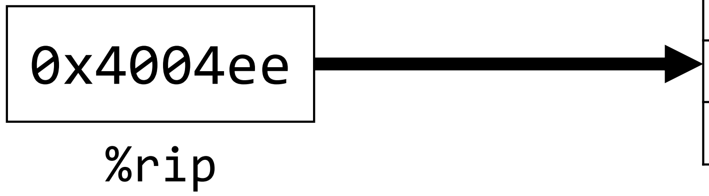

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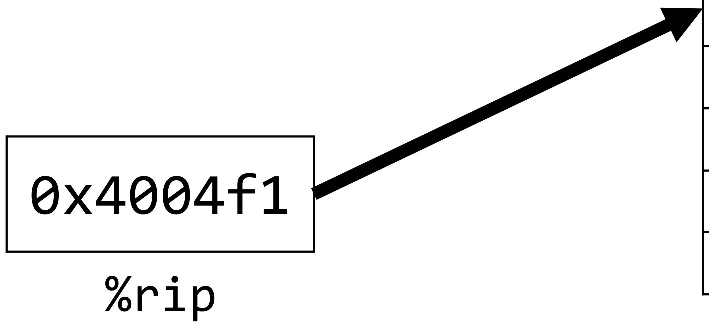

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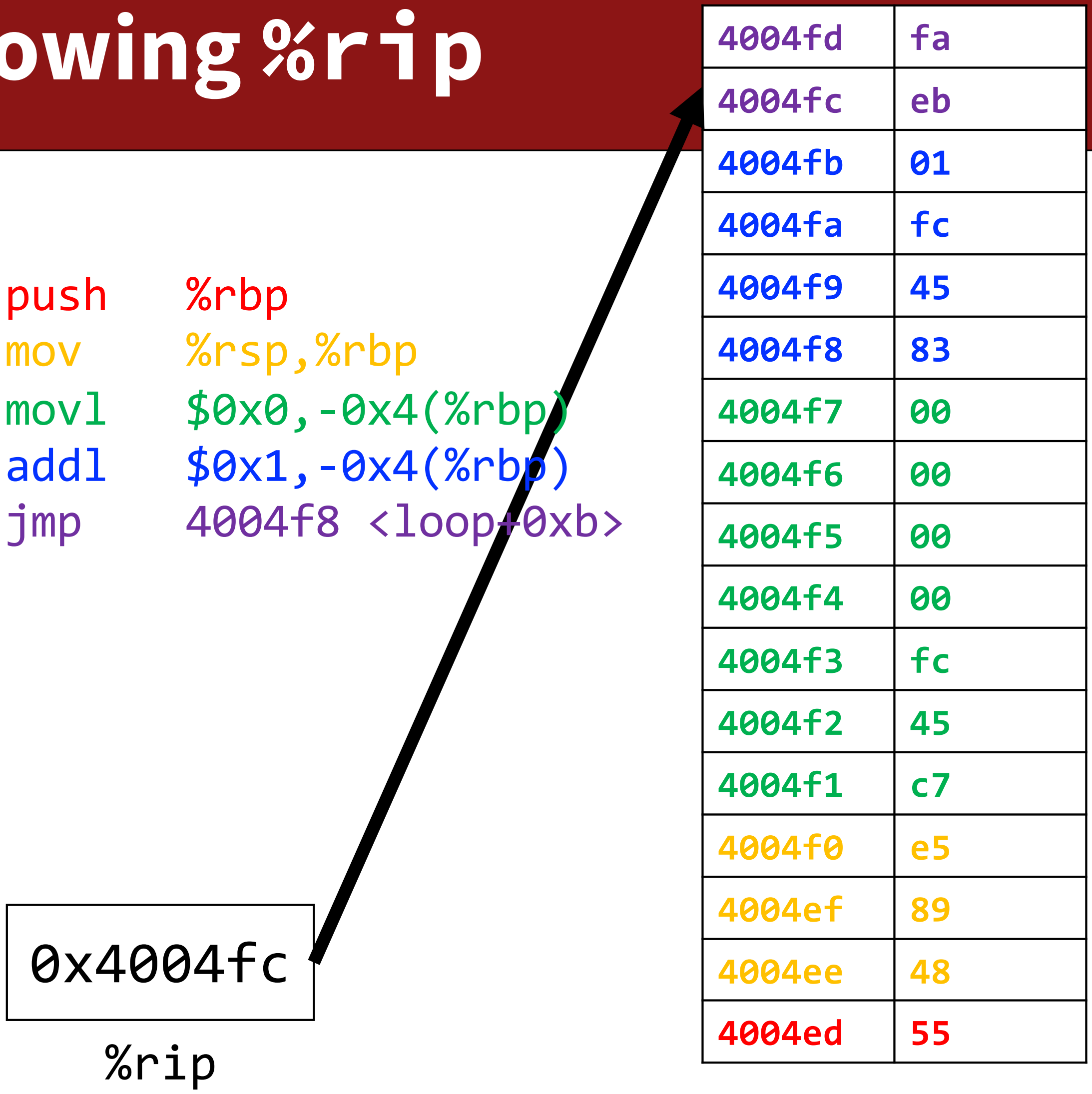

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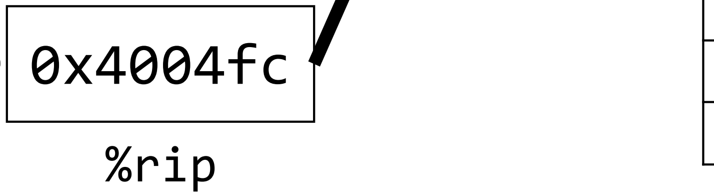
Normally, **dedicated hardware** sets the program counter to the **address of the next instruction**:

`%rip` += current instruction size



Interrupting Control Flow

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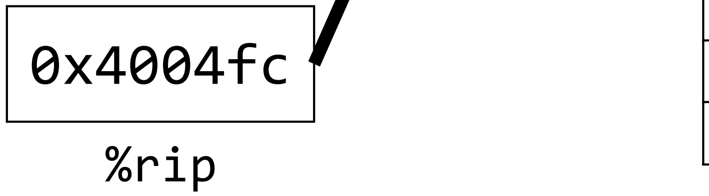
The **`jmp`** instruction is an **unconditional jump** that sets the program counter to the **jump target** (the operand).



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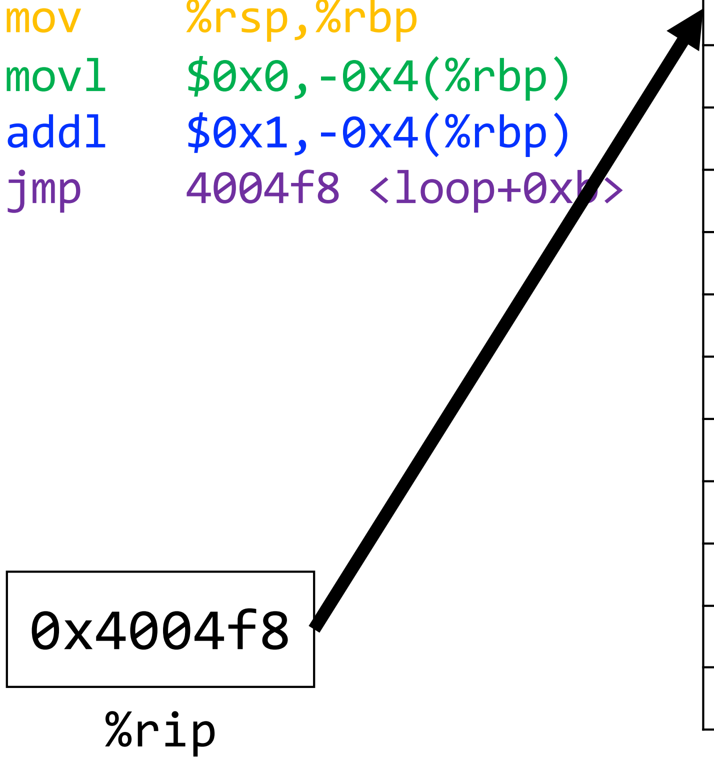

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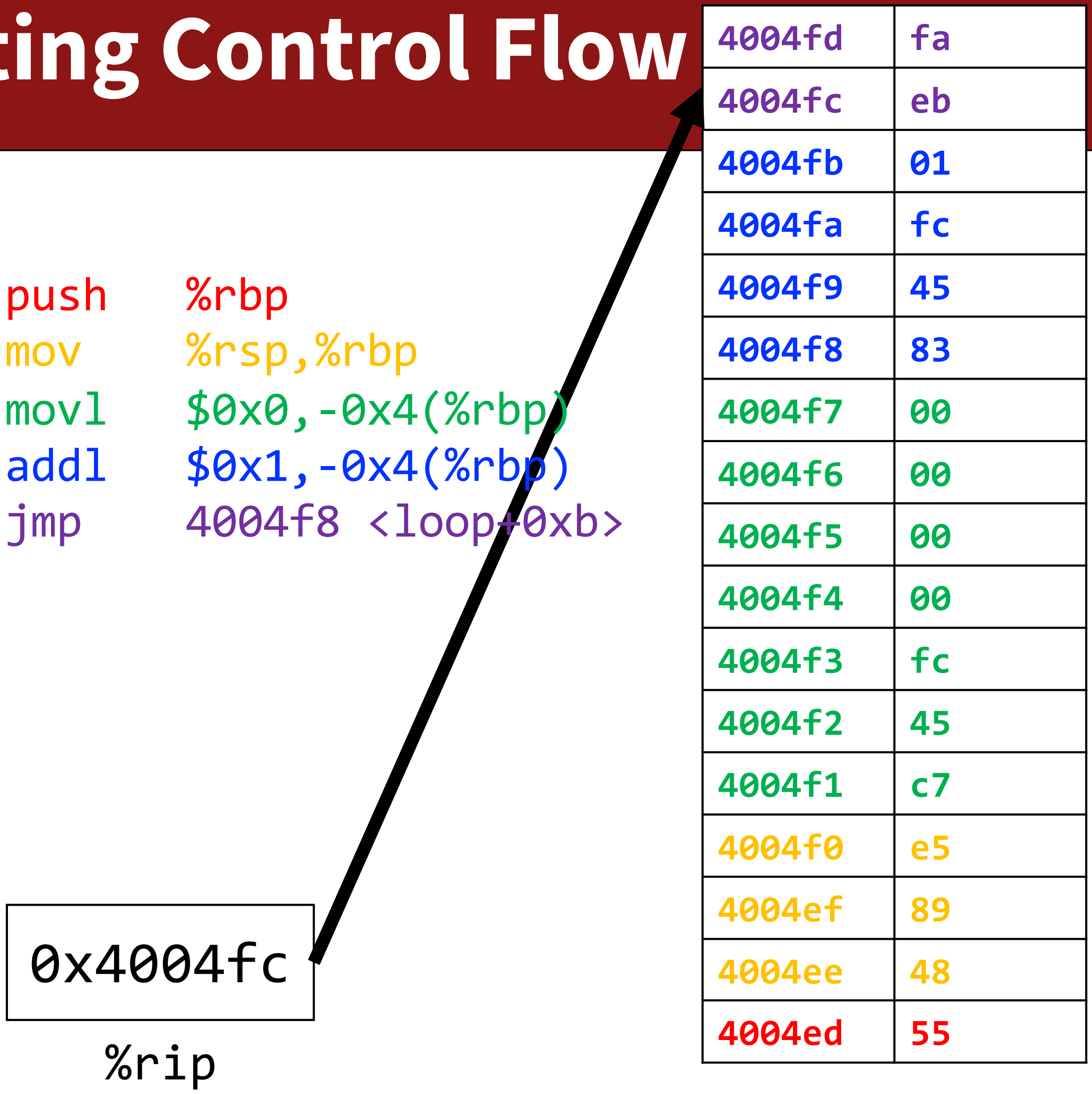

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The above might reverse compile to:

```
int n = 0;
while (true) n++;
...
```

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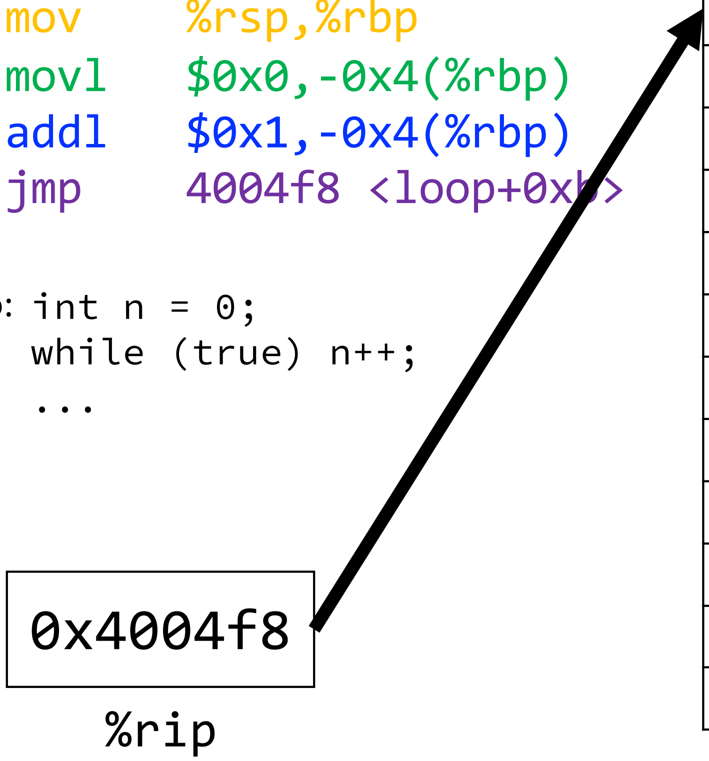

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The `jmp` Instruction

The **`jmp`** instruction jumps to another instruction in the assembly code—an **unconditional jump**.

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

The single operand can be **encoded** directly into the instruction as a **direct jump**:

```
    jmp 404f8 <loop+0xb>
```

The operand can be expressed as an **indirect jump** using one of the **many addressing modes**

```
    jmp *%rax
```

Aside: **Direct, unconditional jumps** are frequently used for **loopbacks** in **for** and **while** loops and for **skipping** around **else** blocks.

Another Aside: **Indirect unconditional jumps** are much less common, used on behalf of very large **switch** statements and function pointers.

Next Question: What if we want to jump **conditionally**?