x86-64 Programming III

CSE 351 Winter 2021

Instructor:

Mark Wyse

Teaching Assistants:

Kyrie Dowling

Catherine Guevara

Ian Hsiao

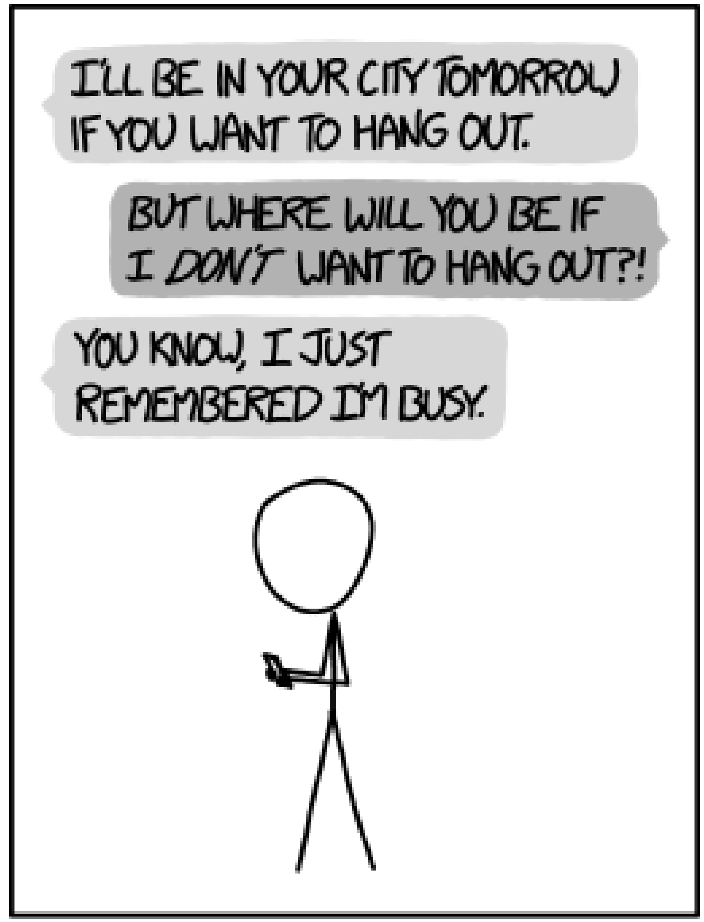
Jim Limprasert

Armin Magness

Allie Pfleger

Cosmo Wang

Ronald Widjaja



WHY I TRY NOT TO BE PEDANTIC ABOUT CONDITIONALS.

http://xkcd.com/1652/

Administrivia

- Study Guide 1 due Friday (1/29)
  - may use late days if needed
- hw9 due Friday, hw10 due Monday
- Lab 2 due next Friday (2/5)

- Section tomorrow on Assembly
  - turn in worksheet by Friday 11:59pm PST

Reading Review

- Terminology:
  - Label, jump target
  - Program counter
  - Jump table, indirect jump

- Any questions from reading?
  - can also post reading questions to Ed Discussion

Aside: movz and movs

width specifiers

`movz__ src, regDest` *# Move with zero extension*

`movs__ src, regDest` *# Move with sign extension*

- Copy from a *smaller* source value to a *larger* destination
- Source can be memory or register; Destination *must* be a register
- Fill remaining bits of dest with **zero** (`movz`) or **sign bit** (`movs`)

movz*SD* / **movs*SD***:

S – size of source (**b** = 1 byte, **w** = 2)

D – size of dest (**w** = 2 bytes, **l** = 4, **q** = 8)

Example:

```
movzbq %al, %rbx
```

0x??	0x??	0x??	0x??	0x??	0x??	0x??	0xFF	←%rax
0x00	0x00	0x00	0x00	0x00	0x00	0x00	0xFF	←%rbx

Aside: `movz` and `movs`

`movz__` *src, regDest* *# Move with zero extension*

`movs__` *src, regDest* *# Move with sign extension*

- Copy from a *smaller* source value to a *larger* destination
- Source can be memory or register; Destination *must* be a register
- Fill remaining bits of dest with **zero** (`movz`) or **sign bit** (`movs`)

`movzSD` / `movsSD`:

S – size of source (**`b`** = 1 byte, **`w`** = 2)

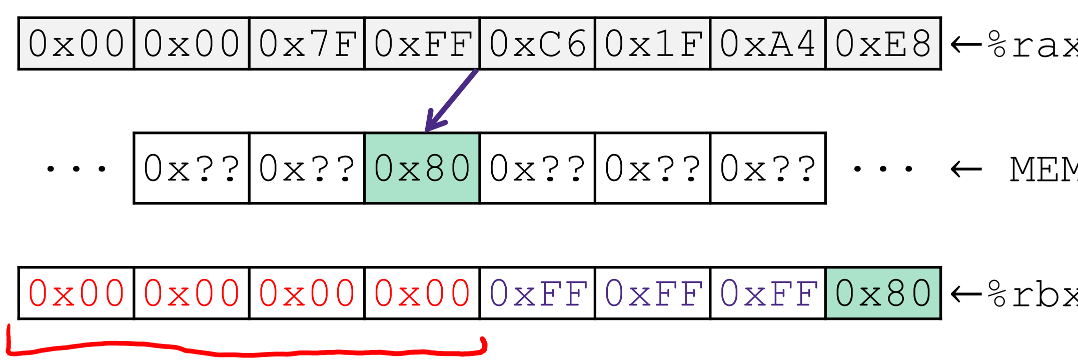
D – size of dest (**`w`** = 2 bytes, **`l`** = 4, **`q`** = 8)

Note: In x86-64, *any instruction* that generates a 32-bit (long word) value for a register also sets the high-order portion of the register to 0. Good example on p. 184 in the textbook.

Example:

`movsbl (%rax), %ebx`

Copy 1 byte from memory into 8-byte register & sign extend it



Using Condition Codes: Jumping

ZF: (r == 0)
SF: (r < 0), MSB == 1
CF: unsigned overflow
OF: signed overflow

- `j*` Instructions
  - Jumps to ***target*** (an address) based on condition codes

Instruction	Condition	Description
`jmp` *target*	`1`	Unconditional
`je` *target*	`ZF`	Equal / Zero
`jne` *target*	`~ZF`	Not Equal / Not Zero
`js` *target*	`SF`	Negative
`jns` *target*	`~SF`	Nonnegative
`jg` *target*	`~(SF^OF)&~ZF`	Greater (Signed)
`jge` *target*	`~(SF^OF)`	Greater or Equal (Signed)
`jl` *target*	`(SF^OF)`	Less (Signed)
`jle` *target*	`(SF^OF)|ZF`	Less or Equal (Signed)
`ja` *target*	`~CF&~ZF`	Above (unsigned ">")
`jb` *target*	`CF`	Below (unsigned "<")

Using Condition Codes: Setting

ZF: (r == 0)
SF: (r < 0), MSB == 1
CF: unsigned overflow
OF: signed overflow

- `set*` Instructions
  - Set low-order byte of `dst` to 0 or 1 based on condition codes
  - Does not alter remaining 7 bytes

Instruction	Condition	Description
sete *dst*	ZF	Equal / Zero
setne *dst*	~ZF	Not Equal / Not Zero
sets *dst*	SF	Negative
setns *dst*	~SF	Nonnegative
setg *dst*	~(SF^OF)&~ZF	Greater (Signed)
setge *dst*	~(SF^OF)	Greater or Equal (Signed)
setl *dst*	(SF^OF)	Less (Signed)
setle *dst*	(SF^OF)|ZF	Less or Equal (Signed)
seta *dst*	~CF&~ZF	Above (unsigned ">")
setb *dst*	CF	Below (unsigned "<")

Choosing instructions for conditionals

- All arithmetic instructions set condition flags based on result of operation (`op`)
  - Conditionals are comparisons against 0
- Come in instruction *pairs*

```
      addq 5, (p)
  je:    *p+5 == 0
  jne:   *p+5 != 0
  jg:    *p+5 >  0
  jl:    *p+5 <  0
```

```
      orq a, b
  je:    b|a == 0
  jne:   b|a != 0
  jg:    b|a >  0
  jl:    b|a <  0
```

		`(op) s, d`
`je`	"Equal"	`d (op) s == 0`
`jne`	"Not equal"	`d (op) s != 0`
`js`	"Sign" (negative)	`d (op) s < 0`
`jns`	(non-negative)	`d (op) s >= 0`
`jg`	"Greater"	`d (op) s > 0`
`jge`	"Greater or equal"	`d (op) s >= 0`
`jl`	"Less"	`d (op) s < 0`
`jle`	"Less or equal"	`d (op) s <= 0`
`ja`	"Above" (unsigned >)	`d (op) s > 0U`
`jb`	"Below" (unsigned <)	`d (op) s < 0U`

Choosing instructions for conditionals

- Reminder: `cmp` is like `sub`, `test` is like `and`
  - Result is not stored anywhere

		cmp a,b	test a,b
je	"Equal"	b == a	b&a == 0
jne	"Not equal"	b != a	b&a != 0
js	"Sign" (negative)	b-a < 0	b&a < 0
jns	(non-negative)	b-a >=0	b&a >= 0
jg	"Greater"	b > a	b&a > 0
jge	"Greater or equal"	b >= a	b&a >= 0
jl	"Less"	b < a	b&a < 0
jle	"Less or equal"	b <= a	b&a <= 0
ja	"Above" (unsigned >)	b $>_U$ a	b&a > 0U
jb	"Below" (unsigned <)	b $<_U$ a	b&a < 0U

```
cmpq 5, (p)
je:  *p == 5
jne: *p != 5
jg:  *p >  5
jl:  *p <  5
```

```
testq a, a
je:  a == 0
jne: a != 0
jg:  a >  0
jl:  a <  0
```

```
testb a, 0x1
```
je: a_{LSB} == 0
jne: a_{LSB} == 1

Choosing instructions for conditionals

		cmp a,b	test a,b
je	"Equal"	b == a	b&a == 0
jne	"Not equal"	b != a	b&a != 0
js	"Sign" (negative)	b-a < 0	b&a < 0
jns	(non-negative)	b-a >=0	b&a >= 0
jg	"Greater"	b > a	b&a > 0
jge	"Greater or equal"	b >= a	b&a >= 0
jl	"Less"	b < a	b&a < 0
jle	"Less or equal"	b <= a	b&a <= 0
ja	"Above" (unsigned >)	b $>_U$ a	b&a > 0U
jb	"Below" (unsigned <)	b $<_U$ a	b&a < 0U

Register	Use(s)
%rdi	argument x
%rsi	argument y
%rax	return value

```
if (x < 3) {
  return 1;
}
return 2;
```

```
  cmpq $3, %rdi
  jge T2
T1: # x < 3:
  movq $1, %rax
  ret
T2: # !(x < 3):
  movq $2, %rax
  ret
```

Practice Question 1

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rax	return value

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

A. `cmpq %rsi, %rdi` / `jle .L4`
B. `cmpq %rsi, %rdi` / `jg .L4`
C. `testq %rsi, %rdi` / `jle .L4`
D. `testq %rsi, %rdi` / `jg .L4`
E. We're lost…

```
absdiff:
    ____________________
    ____________________
                          # x > y:
    movq    %rdi, %rax
    subq    %rsi, %rax
    ret
.L4:                      # x <= y:
    movq    %rsi, %rax
    subq    %rdi, %rax
    ret
```

jump when not (x > y) == when x <= y

Choosing instructions for conditionals

		cmp a,b	test a,b
je	"Equal"	b == a	b&a == 0
jne	"Not equal"	b != a	b&a != 0
js	"Sign" (negative)	b-a < 0	b&a < 0
jns	(non-negative)	b-a >=0	b&a >= 0
jg	"Greater"	b > a	b&a > 0
jge	"Greater or equal"	b >= a	b&a >= 0
jl	"Less"	b < a	b&a < 0
jle	"Less or equal"	b <= a	b&a <= 0
ja	"Above" (unsigned >)	b $>_U$ a	b&a > 0U
jb	"Below" (unsigned <)	b $<_U$ a	b&a < 0U

```
if (x < 3 && x == y) {
  return 1;
} else {
  return 2;
}
```

```
  cmpq $3, %rdi
  setl %al

  cmpq %rsi, %rdi
  sete %bl

  testb %al, %bl
  je T2
T1: # x < 3 && x == y:
  movq $1, %rax
  ret
T2: # else
  movq $2, %rax
  ret
```

- https://godbolt.org/z/Tfrv33

Labels

```
swap:
    movq   (%rdi), %rax
    movq   (%rsi), %rdx
    movq   %rdx, (%rdi)
    movq   %rax, (%rsi)
    ret
```

```
max:
    movq %rdi, %rax
    cmpq %rsi, %rdi
    jg   done
    movq %rsi, %rax
done:
    ret
```

- A jump changes the program counter (`%rip`)
  - `%rip` tells the CPU the *address* of the next instruction to execute
- **Labels** give us a way to refer to a specific instruction in our assembly/machine code
  - Associated with the *next* instruction found in the assembly code (ignores whitespace)
  - Each ***use*** of the label will eventually be replaced with something that indicates the final address of the instruction that it is associated with

x86 Control Flow

- Condition codes
- Conditional and unconditional branches
- **Loops**
- Switches

Expressing with Goto Code

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

```
long absdiff_j(long x, long y)
{
    long result;
    int ntest = (x <= y);
    if (ntest) goto Else;
    result = x-y;
    goto Done;
 Else:
    result = y-x;
 Done:
    return result;
}
```

- C allows goto as means of transferring control (jump)
  - Closer to assembly programming style
  - Generally considered bad coding style

Compiling Loops

C/Java code:

```
while ( sum != 0 ) {
    <loop body>
}
```

Assembly code:

```
loopTop:    testq %rax, %rax
            je    loopDone
            <loop body code>
            jmp   loopTop
loopDone:
```

- Other loops compiled similarly
  - Will show variations and complications in coming slides, but may skip a few examples in the interest of time
- Most important to consider:
  - When should conditionals be evaluated? (*while* vs. *do-while*)
  - How much jumping is involved?

Compiling Loops

While Loop:

C:

```
while ( sum != 0 ) {
    <loop body>
}
```

x86-64:

```
loopTop:    testq %rax, %rax
            je    loopDone
            <loop body code>
            jmp   loopTop
loopDone:
```

Do-while Loop:

first iteration unconditionally execute

C:

```
do {
    <loop body>
} while ( sum != 0 )
```

x86-64:

```
loopTop:
            <loop body code>
            testq  %rax, %rax
            jne    loopTop
loopDone:
```

While Loop (ver. 2):

C:

```
while ( sum != 0 ) {
    <loop body>
}
```

x86-64:

```
            testq %rax, %rax
            je    loopDone
loopTop:
            <loop body code>
            testq %rax, %rax
            jne   loopTop
loopDone:
```

initial comp.

For-Loop → While-Loop

For-Loop:

```
for (Init; Test; Update) {
      Body
}
```

While-Loop Version:

```
Init;
while (Test) {
      Body
      Update;
}
L2:
```

Caveat: C and Java have `break` and `continue`

- Conversion works fine for break
  - Jump to same label as loop exit condition
- But not continue: would skip doing *Update*, which it should do with for-loops
  - Introduce new label at *Update*

Practice Question 2

- The following is assembly code for a for-loop; identify the corresponding parts (Init, Test, Update)
  - i → %eax, x → %rdi, y → %esi

```
       movl    $0, %eax
.L2:   cmpl    %esi, %eax
       jge     .L4
       movslq  %eax, %rdx
       leaq    (%rdi,%rdx,4), %rcx
       movl    (%rcx), %edx
       addl    $1, %edx
       movl    %edx, (%rcx)
       addl    $1, %eax
       jmp     .L2
.L4:
```

x86 Control Flow

- Condition codes
- Conditional and unconditional branches
- Loops
- **Switches**

```
long switch_ex
   (long x, long y, long z)
{
    long w = 1;
    switch (x) {
        case 1:
            w = y*z; break;
        case 2:
            w = y/z;
        /* Fall Through */
        case 3:
            w += z;  break;
        case 5:
        case 6:
            w -= z;  break;
        case 7:
            w = y%z; break;
        default:
            w = 2;
    }
    return w;
}
```

Switch Statement Example

- Multiple case labels
  - Here: 5 & 6
- Fall through cases
  - Here: 2
- Missing cases
  - Here: 4
- Implemented with:
  - *Jump table*
  - *Indirect jump instruction*

Jump Table Structure

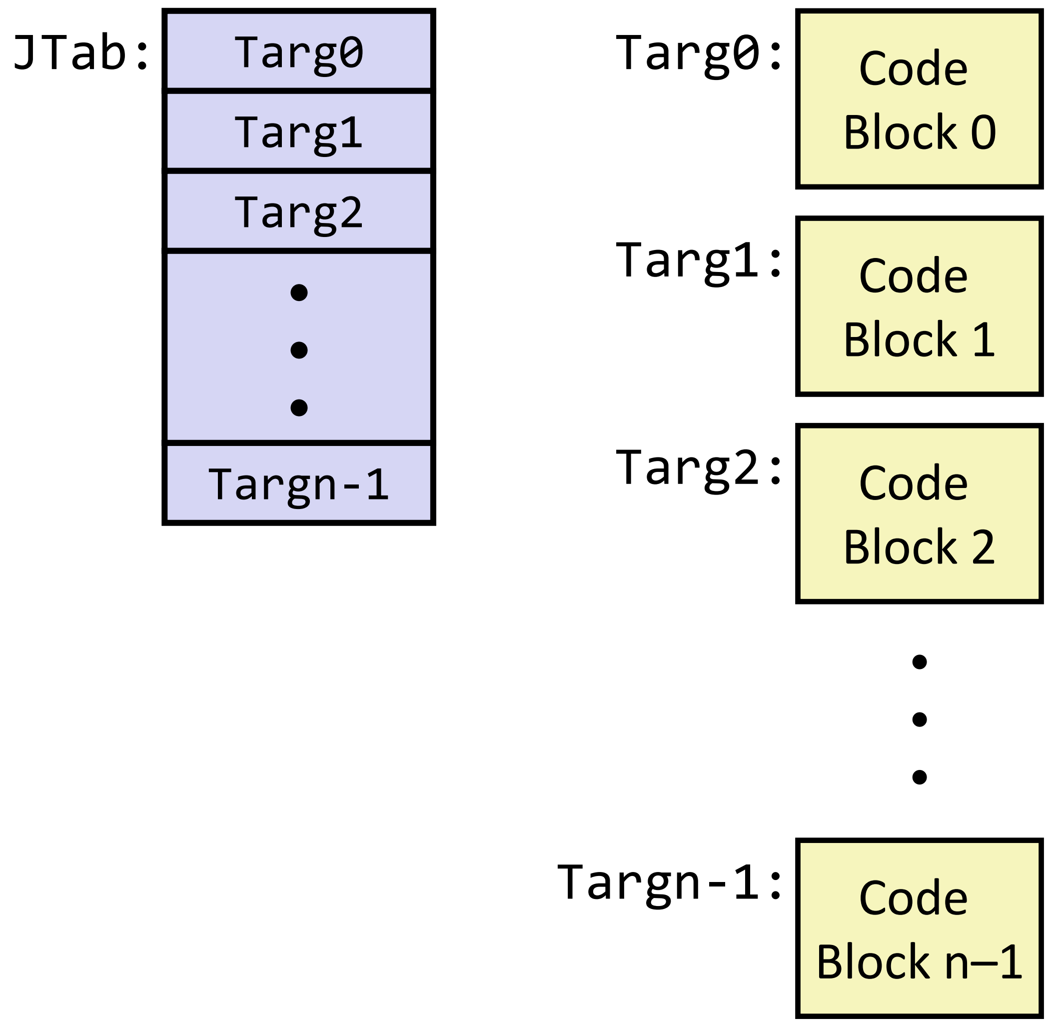
Switch Form

```
switch (x) {
  case val_0:
     Block 0
  case val_1:
     Block 1
     • • •
  case val_n-1:
     Block n–1
}
```

Approximate Translation

```
target = JTab[x];
goto target;
```

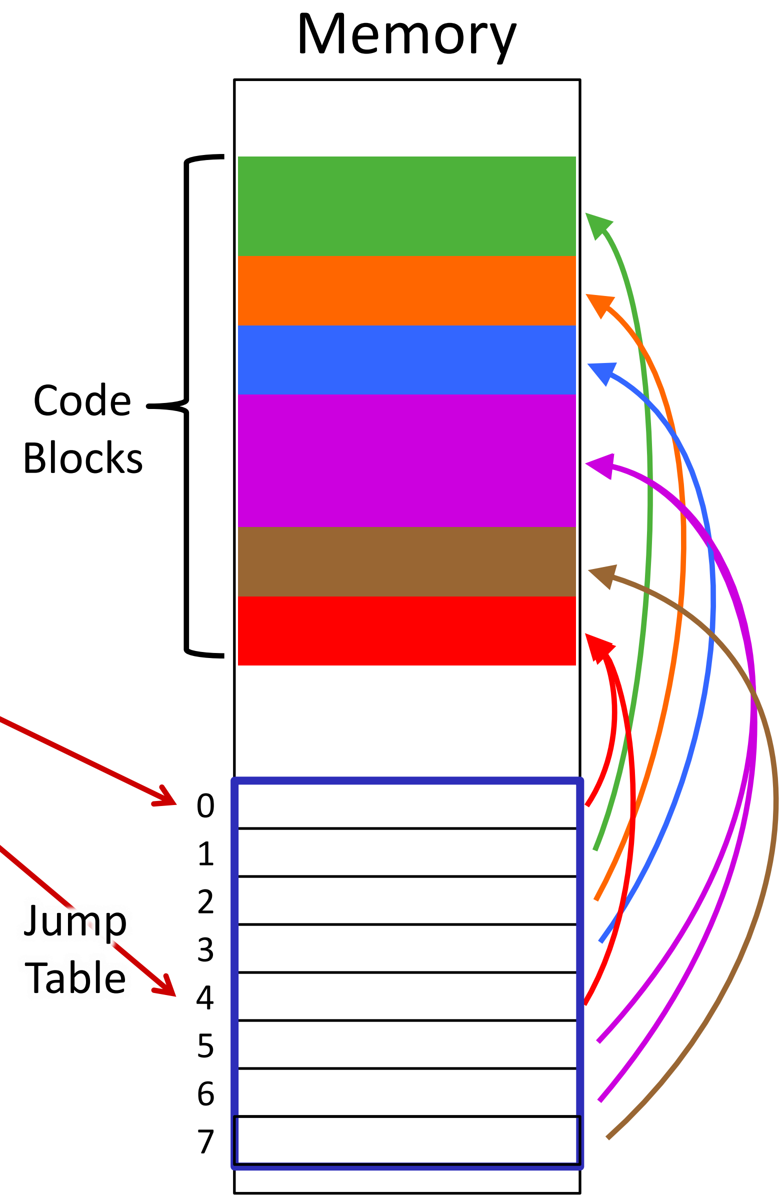
Jump Table / Jump Targets



Jump Table Structure

C code:

```
switch (x) {
  case 1: <code> break;
  case 2: <code>
  case 3: <code> break;
  case 5:
  case 6: <code> break;
  case 7: <code> break;
  default: <code>
}
```



Use the jump table when x ≤ 7:

```
if (x <= 7)
  target = JTab[x];
  goto target;
else
  goto default;
```

Switch Statement Example

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)
%rax	return value

```
long switch_ex(long x, long y, long z)
{
    long w = 1;
    switch (x) {
      . . .
    }
    return w;
}
```

Note compiler chose to not initialize w

```
switch_ex:
    movq    %rdx, %rcx
    cmpq    $7, %rdi         # x:7
    ja      .L9              # default
    jmp     *.L4(,%rdi,8)    # jump table
```

Take a look!
https://godbolt.org/z/Y9Kerb

jump above – unsigned > catches negative default cases

Switch Statement Example

```
long switch_ex(long x, long y, long z)
{
    long w = 1;
    switch (x) {
      . . .
    }
    return w;
}
```

```
switch_ex:
    movq    %rdx, %rcx
    cmpq    $7, %rdi        # x:7
    ja      .L9             # default
    jmp     *.L4(,%rdi,8) # jump table
```

Indirect jump

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad    .L9    # x = 0
  .quad    .L8    # x = 1
  .quad    .L7    # x = 2
  .quad    .L10   # x = 3
  .quad    .L9    # x = 4
  .quad    .L5    # x = 5
  .quad    .L5    # x = 6
  .quad    .L3    # x = 7
```

Assembly Setup Explanation

- Table Structure
  - Each target requires 8 bytes (address)
  - Base address at `.L4`
- **Direct jump:** `jmp .L9`
  - Jump target is denoted by label `.L9`
- **Indirect jump:** `jmp *.L4(,%rdi,8)`
  - Start of jump table: `.L4`
  - Must scale by factor of 8 (addresses are 8 bytes)
  - Fetch target from effective address `.L4 + x*8`
    - Only for $0 \le x \le 7$

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad    .L9    # x = 0
  .quad    .L8    # x = 1
  .quad    .L7    # x = 2
  .quad    .L10   # x = 3
  .quad    .L9    # x = 4
  .quad    .L5    # x = 5
  .quad    .L5    # x = 6
  .quad    .L3    # x = 7
```

GDB Demo

- The `movz` and `movs` examples on a real machine!
  - `movzbq %al, %rbx`
  - `movsbl (%rax), %ebx`

- You will need to use GDB to get through Lab 2
  - Useful debugger in this class and beyond!

- Pay attention to:
  - Setting breakpoints (`break`)
  - Stepping through code (`step`/`next` and `stepi`/`nexti`)
  - Printing out expressions (`print` – works with regs & vars)
  - Examining memory (`x`)