x86-64 Programming IV

CSE 351 Autumn 2024

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Relevant Course

- HW8 due TONIGHT, Wednesday (10/16) @ 11:59 pm
- HW9 due Friday (10/18) @ 11:59 pm
- Lab 2 (x86-64) due next Friday (10/25)
  - GDB Demo Video on Ed!
  - Learn to read x86-64 assembly and use GDB
  - See GDB Tutorial and Phase 1 walkthrough in Section 4!

Conditionals and Control Flow

- Conditional branch/*jump*
  - Jump to somewhere else <u>if some condition is true</u>, otherwise execute next instruction
- Unconditional branch/*jump*
  - <u>Always</u> jump when you get to this instruction

- Together, they can implement most control flow constructs in high-level languages:
  - **`if`** (*condition*) **`then`** {…} **`else`** {…}
  - **`while`** (*condition*) {…}
  - **`do`** {…} **`while`** (*condition*)
  - **`for`** (*initialization*; *condition*; *iterative*) {…}
  - **`switch`** {…}

Conditional Example using `set`

		`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 > a`	`b&a > 0U`
`jb`	"Below" (unsigned <)	`b < 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

Labels & Jumps in C?

```
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

Do not use `goto` in your C code!

- C allows `goto` as means of transferring control (`jump`)
  - Closer to assembly programming style
  - Generally considered bad coding style… **listen to Kernighan & Ritchie:**

> **3.8 Goto and Labels**
>
> C provides the infinitely-abusable **goto** statement, and labels to branch to. Formally, the **goto** is never necessary, and in practice it is almost always easy to write code without it. We have not used **goto** in this book.
>
> Nevertheless, there are a few situations where **goto**s may find a place. The most common is to abandon processing in some deeply nested structure, such as breaking out of two or more loops at once. The **break** statement cannot be used directly since it only exits from the innermost loop. Thus:

x86 Control Flow

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

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:

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:
```

For-Loop → While-Loop

For-Loop:

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

While-Loop Version:

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

<u>Caveat</u>: 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*

Polling Question

- 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:
```

```
for(________; ________; ________)
```

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;
}
```

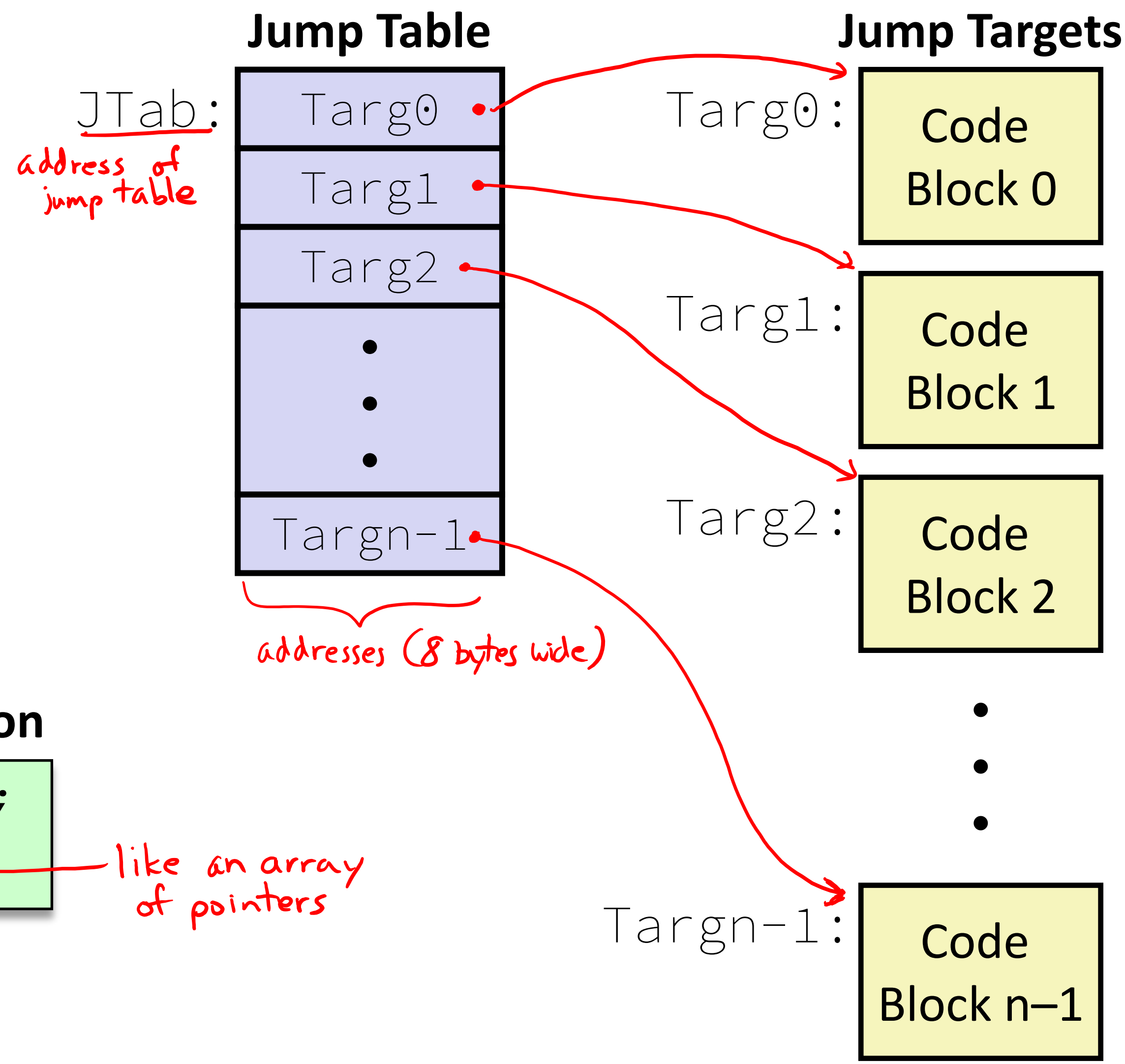
Switch Statement Example

- 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;
```

like an array of pointers

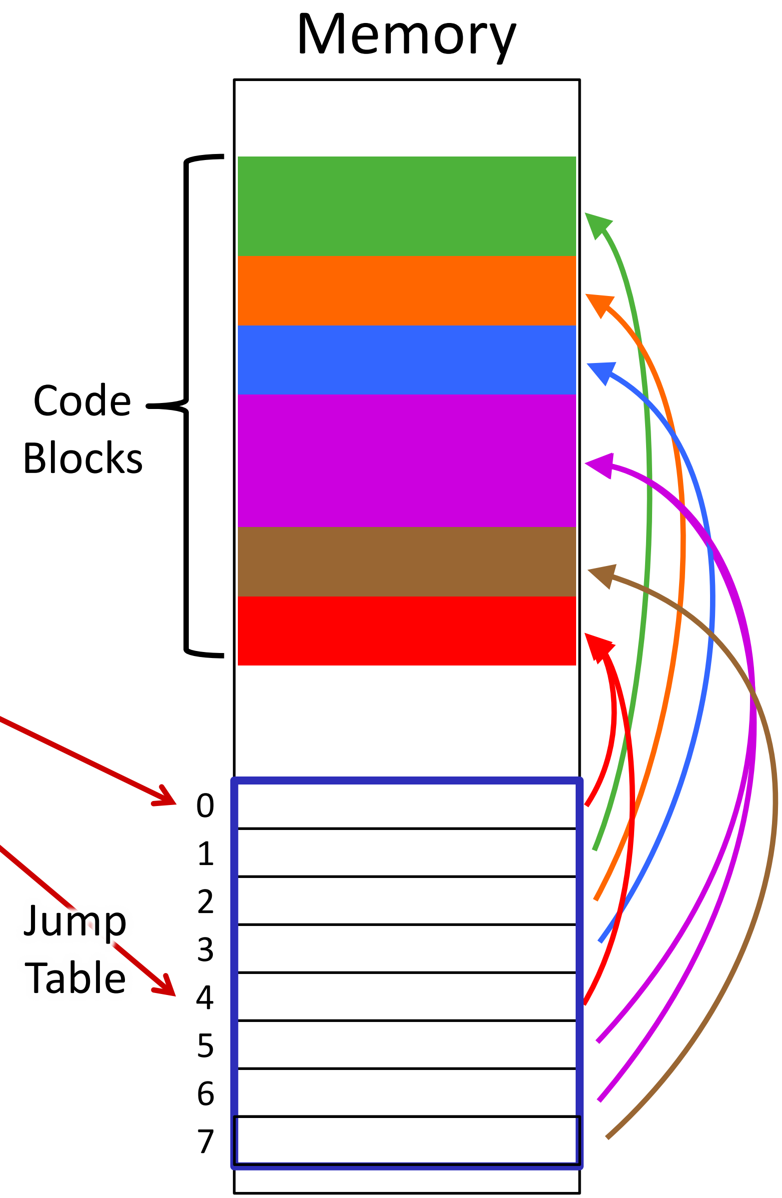
Jump Table Structure

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

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

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

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;
}
```

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
```

address

following data is a "quad word" = 8 bytes

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

Indirect jump

D + Ri * S

addr of jump table

x

sizeof (void*)

Assembly Setup Explanation

- Table Structure
  - Each target requires 8 bytes (address)
  - Base address at `.L4`

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
```

- **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 $0 \le x \le 7$

Summary

- Control flow in x86 determined by Condition Codes
  - Showed **C**arry, **Z**ero, **S**ign, and **O**verflow, though others exist
  - Set flags with arithmetic instructions (implicit) or Compare and Test (explicit)
  - Set instructions read out flag values
  - Jump instructions use flag values to determine next instruction to execute
  - Most control flow constructs (*e.g.*, if-else, for-loop, while-loop) can be implemented in assembly using combinations of conditional and unconditional jumps