

# Machine-Level Programming II: Control

# Outline

- **Control: Condition codes**
- Conditional branches
- Loops
- Switch Statements

# Processor State (x86-64, Partial)

## ■ Information about currently executing program

- Temporary data ( **%rax**, ... )
- Location of runtime stack ( **%rsp** )
- Location of current code control point ( **%rip**, ... )
- Status of recent tests ( **CF**, **ZF**, **SF**, **OF** )

Current stack top

### Registers

%rax	%r8
%rbx	%r9
%rcx	%r10
%rdx	%r11
%rsi	%r12
%rdi	%r13
%rsp	%r14
%rbp	%r15

%rip      Instruction pointer

CF
ZF
SF
OF
Condition codes

# Condition Codes (Implicit Setting)

## ■ Single bit registers

- **CF**      Carry Flag (for unsigned)    **SF** Sign Flag (for signed)
- **ZF**      Zero Flag                            **OF** Overflow Flag (for signed)

## ■ Implicitly set (think of it as side effect) by arithmetic operations

Example: `addq Src, Dest`  $\leftrightarrow$  `t = a+b`

**CF set** if carry out from most significant bit (unsigned overflow)

**ZF set** if `t == 0`

**SF set** if `t < 0` (as signed)

**OF set** if two's-complement (signed) overflow

`(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`

## ■ Not set by `leaq` instruction

# Condition Codes (Explicit Setting: Compare)

## ■ Explicit Setting by Compare Instruction

- `cmpq Src2, Src1`
- `cmpq b, a` like computing `a-b` without setting destination
- **CF set** if carry out from most significant bit (used for unsigned comparisons)
- **ZF set** if `a == b`
- **SF set** if `(a-b) < 0` (as signed)
- **OF set** if two's-complement (signed) overflow  
`(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`

# Condition Codes (Explicit Setting: Test)

## ■ Explicit Setting by Test instruction

- `testq Src2, Src1`
  - `testq b, a` like computing `a&b` without setting destination
- Sets condition codes based on value of `Src1` & `Src2`
- Useful to have one of the operands be a mask
- **ZF set** when `a&b == 0`
- **SF set** when `a&b < 0`

# Reading Condition Codes

## ■ SetX Instructions

- Set low-order byte of destination to 0 or 1 based on combinations of condition codes
- Does not alter remaining 7 bytes

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

# x86-64 Integer Registers

<b>%rax</b>	<b>%a1</b>
<b>%rbx</b>	<b>%b1</b>
<b>%rcx</b>	<b>%c1</b>
<b>%rdx</b>	<b>%d1</b>
<b>%rsi</b>	<b>%si1</b>
<b>%rdi</b>	<b>%di1</b>
<b>%rsp</b>	<b>%sp1</b>
<b>%rbp</b>	<b>%bp1</b>

<b>%r8</b>	<b>%r8b</b>
<b>%r9</b>	<b>%r9b</b>
<b>%r10</b>	<b>%r10b</b>
<b>%r11</b>	<b>%r11b</b>
<b>%r12</b>	<b>%r12b</b>
<b>%r13</b>	<b>%r13b</b>
<b>%r14</b>	<b>%r14b</b>
<b>%r15</b>	<b>%r15b</b>

- Can reference low-order byte



# Reading Condition Codes (Cont.)

## ■ SetX Instructions:

- Set single byte based on combination of condition codes

## ■ One of addressable byte registers

- Does not alter remaining bytes
- Typically use **movzbl** to finish job
  - 32-bit instructions also set upper 32 bits to 0

```
int gt (long x, long y)
{
    return x > y;
}
```

Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rax	Return value

```
cmpq    %rsi, %rdi    # Compare x:y
setg    %al           # Set when >
movzbl  %al, %eax     # Zero rest of %rax
ret
```

# Outline

- Control: Condition codes
- **Conditional branches**
- Loops
- Switch Statements

# Jumping

## ■ jX Instructions

- Jump to different part of code depending on condition codes

jX	Condition	Description
jmp	1	Unconditional
je	ZF	Equal / Zero
jne	$\sim ZF$	Not Equal / Not Zero
js	SF	Negative
jns	$\sim SF$	Nonnegative
jg	$\sim (SF \wedge OF) \ \& \ \sim ZF$	Greater (Signed)
jge	$\sim (SF \wedge OF)$	Greater or Equal (Signed)
jl	$(SF \wedge OF)$	Less (Signed)
jle	$(SF \wedge OF) \   \ ZF$	Less or Equal (Signed)
ja	$\sim CF \ \& \ \sim ZF$	Above (unsigned)
jb	CF	Below (unsigned)

# Conditional Branch Example (Old Style)

## ■ Generation

```
gcc -Og -S -fno-if-conversion control.c
```

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

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

Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rax	Return value

# Expressing with Goto Code

- C allows goto statement
- Jump to position designated by label

```
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;
}
```

# Caveat

- **The compiler does not literally insert GOTO statements as a way of compiling code, but...**
- **GOTO statements are similar to the instructions in x86-64 (and other ISAs) for implementing control, so they are a nice way to explain what's going on.**

# General Conditional Expression Translation (Using Branches)

## C Code

```
val = Test ? Then_Expr : Else_Expr;
```

```
val = x > y ? x - y : y - x;
```

## Goto Version

```
n_test = !Test;  
if (n_test) goto Else;  
val = Then_Expr;  
goto Done;  
Else:  
    val = Else_Expr;  
Done:  
    . . .
```

- Create separate code regions for then & else expressions
- Execute appropriate one

# Using Conditional Moves

## ■ Conditional Move Instructions

- Instruction supports:  
if (Test) Dest  $\leftarrow$  Src
- Supported in post-1995 x86 processors
- GCC tries to use them
  - But, only when known to be safe

## ■ Why?

- Branches are very disruptive to instruction flow through pipelines
- Conditional moves do not require control transfer

## C Code

```
val = Test  
    ? Then_Expr  
    : Else_Expr;
```

## Goto Version

```
result = Then_Expr;  
eval = Else_Expr;  
nt = !Test;  
if (nt) result = eval;  
return result;
```



# Conditional Move Example

```

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

```

Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rax	Return value

absdiff:

```

movq    %rdi, %rax    # x
subq    %rsi, %rax    # result = x-y
movq    %rsi, %rdx
subq    %rdi, %rdx    # eval = y-x
cmpq    %rsi, %rdi    # x:y
cmovle  %rdx, %rax    # if <=, result = eval
ret

```

# Bad Cases for Conditional Move

## Expensive Computations

```
val = Test(x) ? Hard1(x) : Hard2(x);
```

- Both values get computed
- Only makes sense when computations are very simple

## Risky Computations

```
val = p ? *p : 0;
```

- Both values get computed
- May have undesirable effects

## Computations with side effects

```
val = x > 0 ? x*=7 : x+=3;
```

- Both values get computed
- Must be side-effect free

# Outline

- Control: Condition codes
- Conditional branches
- **Loops**
- Switch Statements

# “Do-While” Loop Example

## C Code

```
long pcount_do
(unsigned long x) {
    long result = 0;
    do {
        result += x & 0x1;
        x >>= 1;
    } while (x);
    return result;
}
```

## Goto Version

```
long pcount_goto
(unsigned long x) {
    long result = 0;
    loop:
        result += x & 0x1;
        x >>= 1;
        if(x) goto loop;
    return result;
}
```

- Count number of 1's in argument *x* (“popcount”)
- Use conditional branch to either continue looping or to exit loop

# “Do-While” Loop Compilation

## Goto Version

```
long pcount_goto
(unsigned long x) {
    long result = 0;
loop:
    result += x & 0x1;
    x >>= 1;
    if(x) goto loop;
    return result;
}
```

Register	Use(s)
%rdi	Argument <b>x</b>
%rax	<b>result</b>

```
        movl    $0, %eax    # result = 0
.L2:                                # loop:
        movq    %rdi, %rdx
        andl    $1, %edx    # t = x & 0x1
        addq    %rdx, %rax  # result += t
        shrq    %rdi        # x >>= 1
        jne     .L2         # if (x) goto loop
        rep; ret
```

# General “Do-While” Translation

## C Code

```
do  
    Body  
while (Test) ;
```

## Goto Version

```
loop:  
    Body  
    if (Test)  
        goto loop
```

■ **Body:** {  
     $\text{Statement}_1$ ;  
     $\text{Statement}_2$ ;  
    ...  
     $\text{Statement}_n$ ;  
}

# General “While” Translation #1

- “Jump-to-middle” translation
- Used with -Og

## While version

```
while (Test)  
    Body
```



## Goto Version

```
    goto test;  
loop:  
    Body  
test:  
    if (Test)  
        goto loop;  
done:
```

# While Loop Example #1

## C Code

```
long pcount_while
(unsigned long x) {
    long result = 0;
    while (x) {
        result += x & 0x1;
        x >>= 1;
    }
    return result;
}
```

## Jump to Middle

```
long pcount_goto_jtm
(unsigned long x) {
    long result = 0;
    goto test;
loop:
    result += x & 0x1;
    x >>= 1;
test:
    if(x) goto loop;
    return result;
}
```

- Compare to do-while version of function
- Initial goto starts loop at test



# General “While” Translation #2

## While version

```
while (Test)  
    Body
```

- “Do-while” conversion
- Used with -O1



## Do-While Version

```
if (!Test)  
    goto done;  
do  
    Body  
    while (Test);  
done:
```



## Goto Version

```
if (!Test)  
    goto done;  
loop:  
    Body  
    if (Test)  
        goto loop;  
done:
```

# While Loop Example #2

## C Code

```
long pcount_while
(unsigned long x) {
    long result = 0;
    while (x) {
        result += x & 0x1;
        x >>= 1;
    }
    return result;
}
```

## Do-While Version

```
long pcount_goto_dw
(unsigned long x) {
    long result = 0;
    if (!x) goto done;
loop:
    result += x & 0x1;
    x >>= 1;
    if(x) goto loop;
done:
    return result;
}
```

- Compare to do-while version of function
- Initial conditional guards entrance to loop

# "For" Loop Form

## General Form

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

```
#define WSIZE 8*sizeof(int)
long pcount_for
(unsigned long x)
{
    size_t i;
    long result = 0;
    for (i = 0; i < WSIZE; i++)
    {
        unsigned bit =
            (x >> i) & 0x1;
        result += bit;
    }
    return result;
}
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
    unsigned bit =
        (x >> i) & 0x1;
    result += bit;
}
```

# “For” Loop → While Loop

For Version

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



While Version

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

# For-While Conversion

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
    unsigned bit =
        (x >> i) & 0x1;
    result += bit;
}
```

```
long pcount_for_while
(unsigned long x)
{
    size_t i;
    long result = 0;
    i = 0;
    while (i < WSIZE)
    {
        unsigned bit =
            (x >> i) & 0x1;
        result += bit;
        i++;
    }
    return result;
}
```

# “For” Loop Do-While Conversion

## C Code      Goto Version

```
long pcount_for
(unsigned long x)
{
    size_t i;
    long result = 0;
    for (i = 0; i < WSIZE; i++)
    {
        unsigned bit =
            (x >> i) & 0x1;
        result += bit;
    }
    return result;
}
```

- Initial test can be optimized away

```
long pcount_for_goto_dw
(unsigned long x) {
    size_t i;
    long result = 0;
    i = 0; Init
    if (!(i < WSIZE)) ! Test
    goto done;
loop:
{
    unsigned bit =
        (x >> i) & 0x1; Body
    result += bit;
}
i++; Update
if (i < WSIZE) Test
    goto loop;
done:
    return result;
}
```

# Outline

- Control: Condition codes
- Conditional branches
- Loops
- **Switch Statements**

```

long switch_eg
(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;
    default:
        w = 2;
    }
    return w;
}

```

# Switch Statement Example

- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

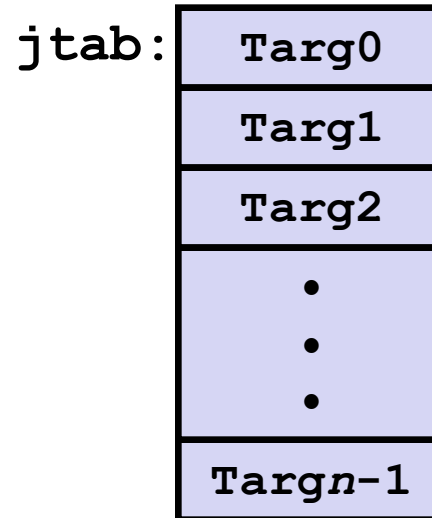


# Jump Table Structure

## Switch Form

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

## Jump Table



## Jump Targets

Targ0:

Code Block  
0

Targ1:

Code Block  
1

Targ2:

Code Block  
2

•  
•  
•

Targn-1:

Code Block  
n-1

## Translation (Extended C)


```
goto *JTab[x];
```

# Switch Statement Example

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

Setup:

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi    # x:6
    ja      .L8
    jmp     *.L4(, %rdi, 8)
```



What range of values  
takes default?

Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rdx	Argument <b>z</b>
%rax	Return value

Note that **w** not  
initialized here

# Switch Statement Example

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

## Jump table

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

## Setup:

```
switch_eg:
    movq      %rdx, %rcx
    cmpq      $6, %rdi      # x:6
    ja        .L8           # Use default
    jmp       *.L4(,%rdi,8)  # goto *JTab[x]
```

*Indirect  
jump*



# Assembly Setup Explanation

## ■ Table Structure

- Each target requires 8 bytes
- Base address at `.L4`

## ■ Jumping

- **Direct:** `jmp .L8`
- Jump target is denoted by label `.L8`
- **Indirect:** `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  $0 \leq x \leq 6$

## Jump table

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

# Jump Table

## Jump table

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

```
switch(x) {
case 1:      // .L3
    w = y*z;
    break;
case 2:      // .L5
    w = y/z;
    /* Fall Through */
case 3:      // .L9
    w += z;
    break;
case 5:
case 6:      // .L7
    w -= z;
    break;
default:    // .L8
    w = 2;
}
```

# Code Blocks (x == 1)

```
switch(x) {
case 1:      // .L3
    w = y*z;
    break;

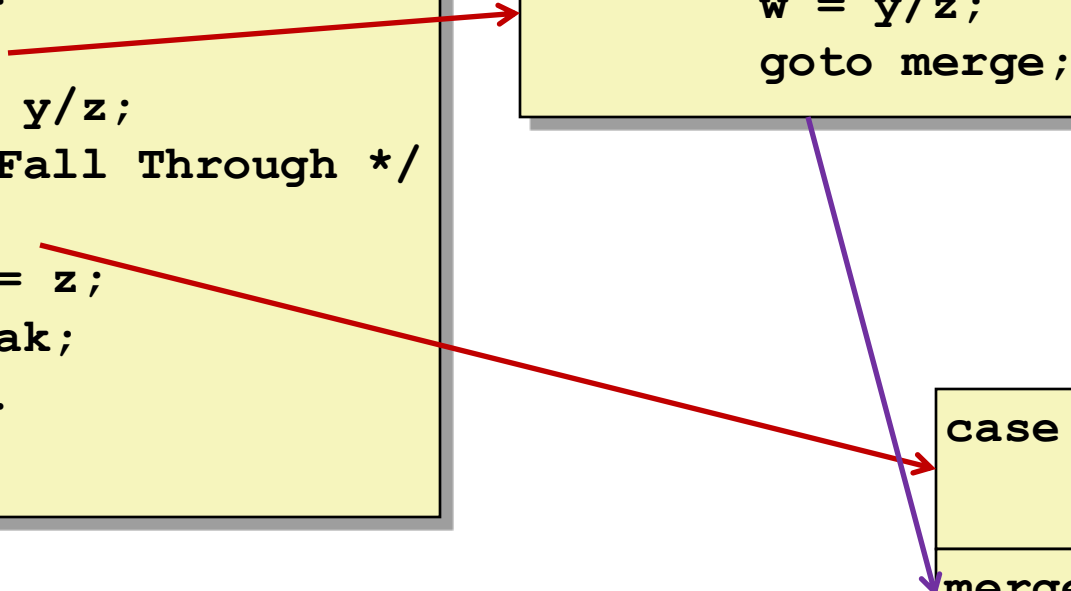
    . . .
}
```

```
.L3:
    movq    %rsi, %rax    # y
    imulq   %rdx, %rax    # y*z
    ret
```

Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rdx	Argument <b>z</b>
%rax	Return value

# Handling Fall-Through

```
long w = 1;  
.  
.  
.  
switch(x) {  
.  
.  
.  
case 2:   
    w = y/z;  
    /* Fall Through */  
case 3:   
    w += z;  
    break;  
.  
.  
.  
}
```



```
case 2:  
    w = y/z;  
    goto merge;
```

```
case 3:  
    w = 1;  
merge:  
    w += z;
```

# Code Blocks (x == 2, x == 3)

```

long w = 1;
. . .
switch(x) {
. . .
case 2:
    w = y/z;
    /* Fall Through */
case 3:
    w += z;
    break;
. . .
}

```

```

.L5:                                # Case 2
    movq    %rsi, %rax
    cqto
    idivq   %rcx                    # y/z
    jmp     .L6                    # goto merge
.L9:                                # Case 3
    movl    $1, %eax               # w = 1
.L6:                                # merge:
    addq    %rcx, %rax             # w += z
    ret

```

Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rdx	Argument <b>z</b>
%rax	Return value



# Code Blocks (x == 5, x == 6, default)

```
switch(x) {
    . . .
    case 5:  // .L7
    case 6:  // .L7
        w -= z;
        break;
    default: // .L8
        w = 2;
}
```

```
.L7:                                # Case 5,6
    movl    $1, %eax                # w = 1
    subq    %rdx, %rax              # w -= z
    ret
.L8:                                # Default:
    movl    $2, %eax                # 2
    ret
```

Register	Use(s)
%rdi	Argument <b>x</b>
%rsi	Argument <b>y</b>
%rdx	Argument <b>z</b>
%rax	Return value

# Summary

## ■ C Control

- if-then-else
- do-while
- while, for
- switch

## ■ Assembler Control

- Conditional jump
- Conditional move
- Indirect jump (via jump tables)
- Compiler generates code sequence to implement more complex control

## ■ Standard Techniques

- Loops converted to do-while or jump-to-middle form
- Large switch statements use jump tables
- Sparse switch statements may use decision trees (if-elseif-elseif-else)