

Machine-Level Programming II: Control

15-213: Introduction to Computer Systems
6th Lecture, Sep. 17, 2015

Instructors:

Randal E. Bryant and David R. O'Hallaron

Today

- **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

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

`%rip` Instruction pointer

<code>CF</code>	<code>ZF</code>	<code>SF</code>	<code>OF</code>
-----------------	-----------------	-----------------	-----------------

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
sete	ZF	Equal / Zero
setne	$\sim ZF$	Not Equal / Not Zero
sets	SF	Negative
setns	$\sim SF$	Nonnegative
setg	$\sim (SF \wedge OF) \ \& \ \sim ZF$	Greater (Signed)
setge	$\sim (SF \wedge OF)$	Greater or Equal (Signed)
setl	$(SF \wedge OF)$	Less (Signed)
setle	$(SF \wedge OF) \ \ ZF$	Less or Equal (Signed)
seta	$\sim CF \ \& \ \sim ZF$	Above (unsigned)
setb	CF	Below (unsigned)

x86-64 Integer Registers

<code>%rax</code>	<code>%al</code>
<code>%rbx</code>	<code>%bl</code>
<code>%rcx</code>	<code>%cl</code>
<code>%rdx</code>	<code>%dl</code>
<code>%rsi</code>	<code>%sil</code>
<code>%rdi</code>	<code>%dil</code>
<code>%rsp</code>	<code>%spl</code>
<code>%rbp</code>	<code>%bpl</code>

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

- 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)
<code>%rdi</code>	Argument x
<code>%rsi</code>	Argument y
<code>%rax</code>	Return value

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

Today

- 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	$(SF \wedge OF) \mid ZF$	Less or Equal (Signed)
ja	$\sim CF \ \& \ \sim ZF$	Above (unsigned)
jb	CF	Below (unsigned)

Conditional Branch Example (Old Style)

■ Generation

```
shark> 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 x
%rsi	Argument y
%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;
}
```

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 x
%rsi	Argument y
%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

Today

- 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 x
%rax	result

```
        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:** {
 Statement_1 ;
 Statement_2 ;
 ...
 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;
}
```

Today

- 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

jtab:	Targ0
	Targ1
	Targ2
	•
	•
	•
	Targn-1

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 x
%rsi	Argument y
%rdx	Argument z
%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

Indirect jump  jmp *.L4(,%rdi,8) # goto *JTab[x]

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 x
%rsi	Argument y
%rdx	Argument z
%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 x
%rsi	Argument y
%rdx	Argument z
%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 x
%rsi	Argument y
%rdx	Argument z
%rax	Return value

Summarizing

■ 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)

Summary

■ Today

- Control: Condition codes
- Conditional branches & conditional moves
- Loops
- Switch statements

■ Next Time

- Stack
- Call / return
- Procedure call discipline