CS 105

"Tour of the Black Holes of Computing"

Machine-Level Programming II: Control Flow

Topics

- Condition codes
- Conditional branches
- Loops
- Switch statements

Condition Codes (Implicit Setting)

Single-bit registers

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

Implicitly set (as side effect) by arithmetic operations

`addq` *Src,Dest*

C analog: `dest += src;`

- CF set if carry out from most significant bit
  - Detects unsigned overflow; also used for multiprecision arithmetic
- ZF set if `src+dest == 0`
- SF set if `src+dest < 0`
- OF set if two's complement overflow

```
(src > 0 && dest > 0 && src+dest < 0) \
  || (src < 0 && dest < 0 && src+dest >= 0)
```

Not **set by `leaq` instruction**

Condition Codes (Explicit Setting)

Explicit setting by Compare instruction

`cmpq` *Src2,Src1*

- `cmpq b,a` like computing `a-b` without setting destination
  - Note reversed operand order!
- CF set if carry out from most significant bit
  - Used for unsigned comparisons
  - Also good for multi-precision arithmetic (at assembly level)
- ZF set if `a == b`
- SF set if `(a-b) < 0`
- OF set if two's complement overflow

```
(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)
```


Condition Codes (Explicit Setting)

Explicit setting by Test instruction

`testq` *Src1,Src2*

- Sets condition codes based on value of *Src1* `&` *Src2*
  - Intel thought it useful to have one operand be a mask
  - Compiler usually sets *Src1* and *Src2* the same
- `testq a,b` like computing `a&b` without setting destination

- ZF set when `a&b == 0`
- SF set when `a&b < 0`
- CF, OF unaffected (not cleared!)

- Most common usage: `testq %rax,%rax`
  - Sets ZF if `%rax == 0`, SF if `%rax < 0`
  - I.e., "Is `%rax` zero, negative, or positive?"

This is the one that matters!

Reading Condition Codes

SetX instructions

- Set single byte based on combinations of condition codes
- Remaining 7 bytes unaltered!

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

x86-64 Integer Registers

%rax	%al	%r8	%r8b
%rbx	%bl	%r9	%r9b
%rcx	%cl	%r10	%r10b
%rdx	%dl	%r11	%r11b
%rsi	%sil	%r12	%r12b
%rdi	%dil	%r13	%r13b
%rsp	%spl	%r14	%r14b
%rbp	%bpl	%r15	%r15b

- Can reference low-order byte

Reading Condition Codes (Cont.)

SetX instructions

- Set single byte based on combinations of condition codes

One of 8 addressable *byte* registers

- Does not alter remaining 3 bytes!
- Typically use `movzbl` to finish job
  - "1" instructions also set upper 32 bits (of 64) to 0

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

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	Return value

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

Note inverted ordering!

Jumping

jX instructions

- Jump to different part of code depending on condition codes

jX	Condition	Description
jmp	1	Unconditional
je/jz	ZF	Equal / Zero
jne/jnz	~ZF	Not Equal / Not Zero
js	SF	Negative
jns	~SF	Nonnegative
jg	~(SF^OF)&~ZF	Greater (signed)
jge	~(SF^OF)	Greater or Equal (signed)
jl	(SF^OF)	Less (signed)
jle	(SF^OF)|ZF	Less or Equal (signed)
ja	~CF&~ZF	Above (unsigned)
jb	CF	Below (unsigned)

Conditional-Branch Example (Old Style)

Generation

```
wilkes> 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

Sinful!

```
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;
    return result;
 Else:
    result = y-x;
    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

```
  ntest = !Test;
  if (ntest) 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 ← Src
- Supported in post-1995 x86 processors
- GCC tries to use them
  - But, only when known to be safe

Why?

- Branches are disruptive to instruction flow through pipelines
- Branches can kill performance
- 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) ? Hard_1(x) : Hard_2(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

"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" or "bitcount")

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:

```
{
  Statement1;
  Statement2;
    …
  Statementn;
}
```


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 Version

```
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 and above`

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(long)
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

```
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;
}
```

Goto Version

```
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;
    result += bit;          Body
  }
  i++;                      Update
  if (i < WSIZE)            Test
    goto loop;
 done:
  return result;
}
```

Initial test can often be optimized away


```
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
```

Approximate Translation

```
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 option?

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

Note that w is not initialized here!

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)
```

Indirect jump

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
```


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 $0 \le x \le 6$

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;
}
```

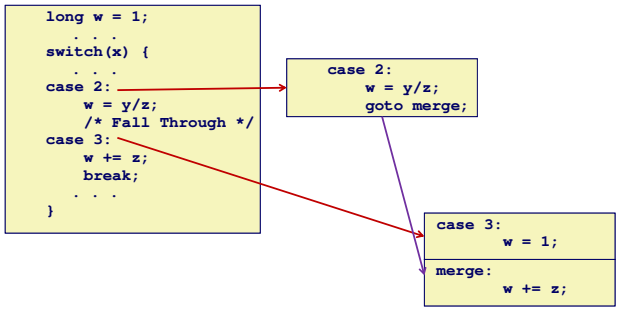

Code Blocks (x == 1)

```
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



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

Sparse Switches

What if jump table is too large?

- Compiler uses if-then-else structure
- Ternary tree gives O(log n) performance