Machine-Level Programming II: Control

15-213: Introduction to Computer Systems
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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)

Registers

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

Current stack top

`%rip`	Instruction pointer

CF	ZF	SF	OF	Condition codes
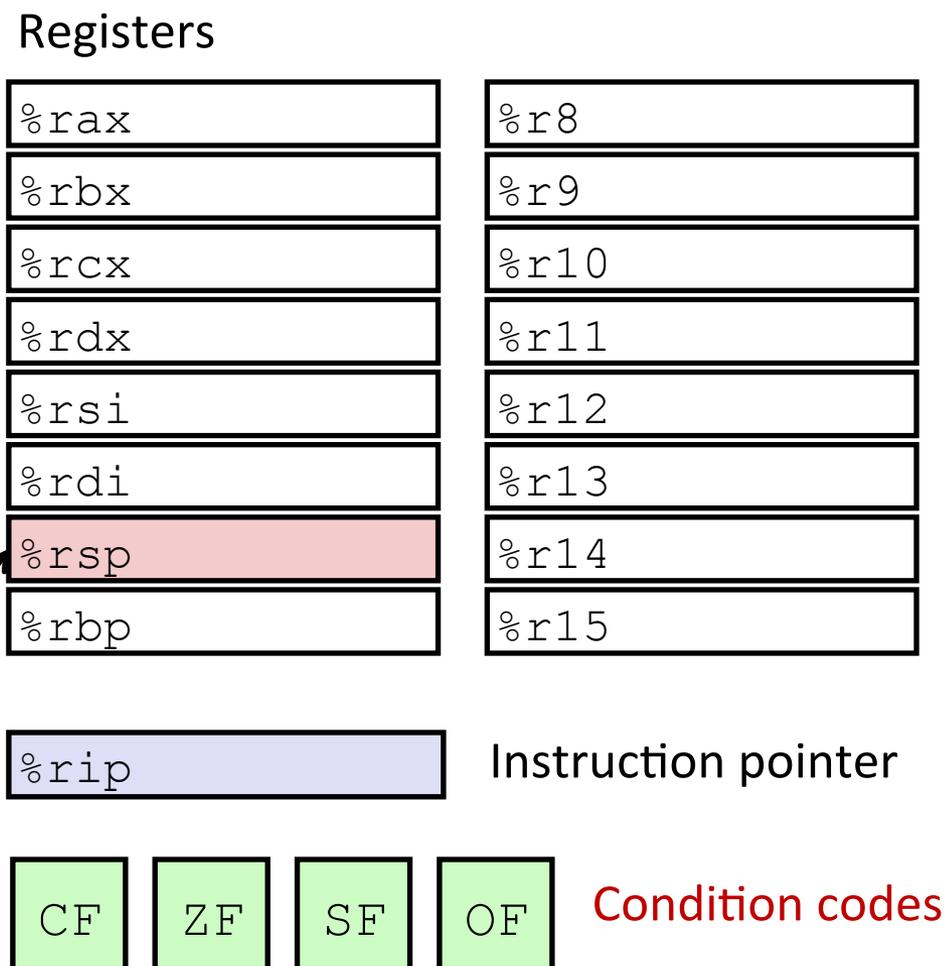
Condition Codes (Implicit Setting)

- **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
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 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 **x**
`%rsi`	Argument **y**
`%rax`	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`	`~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

  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

```
  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 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

Bryant and O'Hallaron, Computer Systems: A Programmer's Perspective, Third Edition

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

General "While" Translation #1

- "Jump-to-middle" translation
- Used with **-Og**

Goto Version

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

While version

```
while (Test)
   Body
```

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
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

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

```
#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;
}
```

"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

Goto Version

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;
}
```

■ 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))
    goto done;               !Test
 loop:
  {
    unsigned bit =
      (x >> i) & 0x1;        Body
    result += bit;
  }
  i++;    Update
  if (i < WSIZE)
    goto loop;               Test
 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
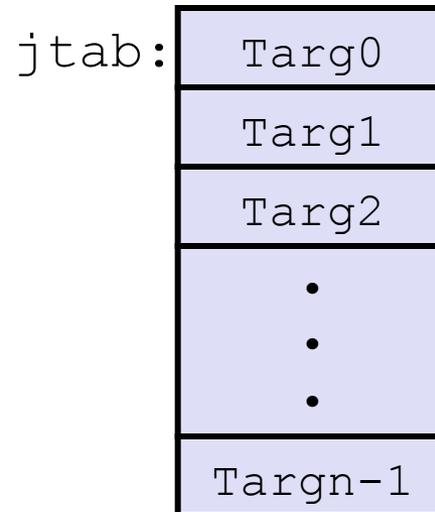
Jump Targets

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)
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rdx	Argument z
%rax	Return value
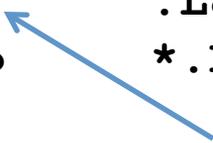
What range of values takes default?

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 **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