# Machine-level Programming II: Control

'20H2

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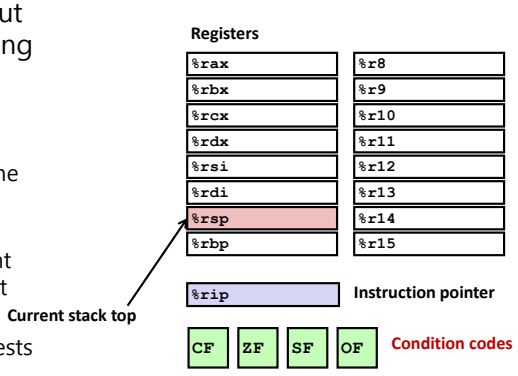
## Outline

- 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** )






## Condition Codes (Implicit Setting)

- Single bit registers
  - **CF** Carry Flag (for unsigned)
  - **ZF** Zero Flag
  - **SF** Sign Flag (for signed)
  - **OF** Overflow Flag (for signed)
- Implicitly set (think of it as side effect) by arithmetic operations
  Example: **addq** *Src,Dest* ↔ **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
```



# 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 | ~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 f or 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



# Outline

- Control: Condition codes
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# "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**

**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 V**

```
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 Version**

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

**Goto Version**

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

- "Do-while" conversion
- Used with **-O1**

# 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 goto starts loop at test



# "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**

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

- Initial test can be optimized aw ay



# Outline

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

# Switch Statement Example

```
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;
}
```

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



# Jump Table Structure

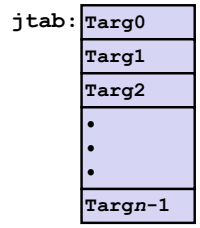
**Switch Form**

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

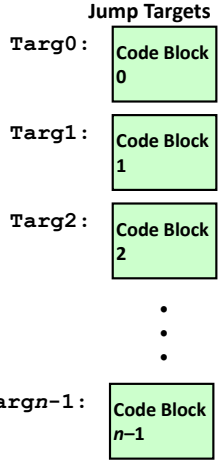
**Translation (Extended C)**

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

**Jump Table**




**Jump Targets**






# 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;
}
```

**Setup:**

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

*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

```
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)



# Questions?