CS 33

Machine Programming (2)

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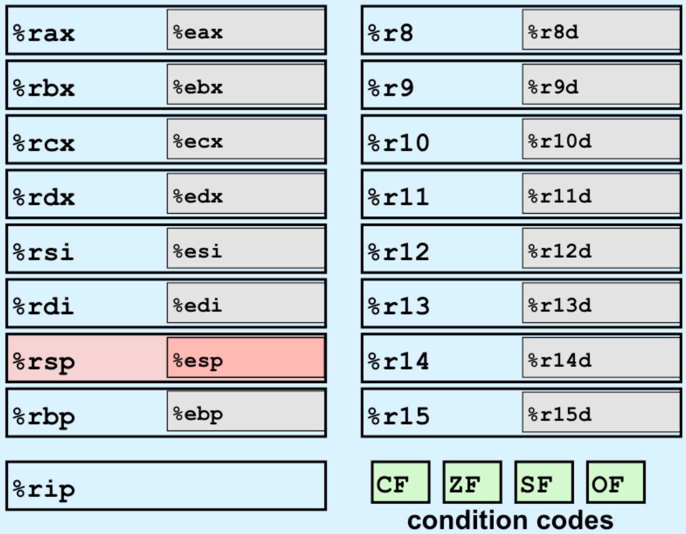
Most of the slides in this lecture are either from or adapted from slides provided by the authors of the textbook "Computer Systems: A Programmer's Perspective," 2nd Edition and are provided from the website of Carnegie-Mellon University, course 15-213, taught by Randy Bryant and David O'Hallaron in Fall 2010. These slides are indicated "Supplied by CMU" in the notes section of the slides.

Processor State (x86-64, Partial)



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: *`addl/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 `lea` instruction**

Supplied by CMU.

Condition Codes (Explicit Setting: Compare)

- **Explicit setting by compare instruction**

  `cmpl/cmpq` **src2, src1**

  `cmpl b,a` **like computing** `a-b` **without setting destination**

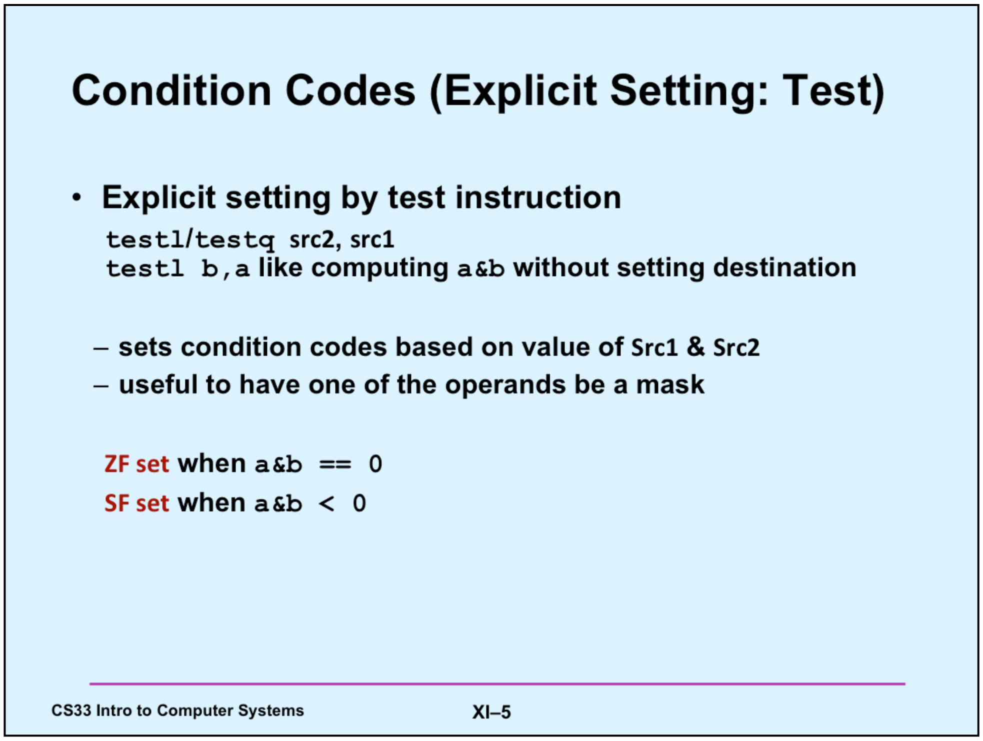
  CF set if carry out from most significant bit (used for unsigned comparisons)

  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)`

Supplied by CMU.



Supplied by CMU.

Reading Condition Codes

- **SetX instructions**
  - **set single byte based on combinations of condition codes**

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)

Supplied by CMU.

Reading Condition Codes (Cont.)

- **SetX instructions:**
  - set single byte based on combination of condition codes
- **Uses one of 8 addressable byte registers**
  - does not alter remaining 7 bytes
  - typically use `movzbl` to finish job

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

%rax	%eax	%ah	%al

Body

```
cmpl %esi, %edi     # compare x : y
setg %al            # %al = x > y
movzbl %al, %eax    # zero rest of %eax/%rax
```


Supplied by CMU, but converted to x86-64.

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)

Supplied by CMU.

Jumping

- **jX instruction**
  - **Jump to differ**

Quiz 1

What would be an appropriate description if the condition is ~CF?

a) above or equal (unsigned)
b) not less (signed)
c) incomparable

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)

Supplied by CMU.

Conditional-Branch Example

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

```
absdiff:
    movl    %esi, %eax
    cmpl    %esi, %edi
    jle     .L6
    subl    %eax, %edx
    movl    %edx, %eax
    jmp .L7
.L6:
    subl %edx, %eax
.L7:
    ret
```

Body1

Body2a

Body2b

Supplied by CMU, but converted to x86-64.

Conditional-Branch Example (Cont.)

```c
int goto_ad(int x, int y)
{
  int result;
  if (x <= y) goto Else;
  result = x-y;
  goto Exit;
Else:
  result = y-x;
Exit:
  return result;
}
```

```
absdiff:
    movl   %esi, %eax
    cmpl   %esi, %edi        Body1
    jle    .L6
    subl   %eax, %edx
    movl   %edx, %eax        Body2a
    jmp .L7
.L6:
    subl %edx, %eax          Body2b
.L7:
    ret
```

- **C allows "goto" as means of transferring control**
  - **closer to machine-level programming style**
- **Generally considered bad coding style**

Supplied by CMU, but converted to x86-64.

General Conditional-Expression Translation

C Code

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

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

Goto Version

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

- Test is expression returning integer
  - == 0 interpreted as false
  - ≠ 0 interpreted as true
- Create separate code regions for then & else expressions
- Execute appropriate one

Supplied by CMU.

Using Conditional Moves

- **Conditional move instructions**
  - instruction supports:
    if (Test) Dest ← Src
  - supported in post-1995 x86 processors
  - gcc does not always use them
    - » wants to preserve compatibility with ancient processors
    - » enabled for x86-64
    - » use switch `–march=686` for IA32
- **Why use them?**
  - 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

```
  tval = Then_Expr;
  result = Else_Expr;
  t = Test;
  if (t) result = tval;
  return result;
```


Supplied by CMU.

Note that, as shown in the goto version, both the then_expr and the else_expr are computed before the test is done.

Conditional Move Example: x86-64

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

x in %edi

y in %esi

```
absdiff:
  movl    %edi, %eax
  subl    %esi, %eax   # result = x-y
  movl    %esi, %edx
  subl    %edi, %edx   # tval = y-x
  cmpl    %esi, %edi   # compare x:y
  cmovle  %edx, %eax   # if <=, result = tval
  ret
```


Supplied by CMU.

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

Supplied by CMU.

"Do-While" Loop Example

C Code

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

Goto Version

```
int pcount_do(unsigned x)
{
  int 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 either to continue looping or to exit loop**

Supplied by CMU.

"Do-While" Loop Compilation

Goto Version

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

Registers:

%edx	x
%eax	result

```
  movl   $0, %eax      #   result = 0
.L2:                   # loop:
  movl   %edx, %ecx
  andl   $1, %ecx      #   t = x & 1
  addl   %ecx, %eax    #   result += t
  shrl   %edx          #   x >>= 1
  jne    .L2           #   if !0, goto loop
```


Supplied by CMU.

Note that the condition codes are set as part of the execution of the shrl instruction.

General "Do-While" Translation

C Code

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

Goto Version

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

- **Body:**
```
{
  Statement1;
  Statement2;
    …
  Statementn;
}
```
- **Test returns integer**
  - **= 0 interpreted as false**
  - **≠ 0 interpreted as true**

Supplied by CMU.

“While” Loop Example

C Code

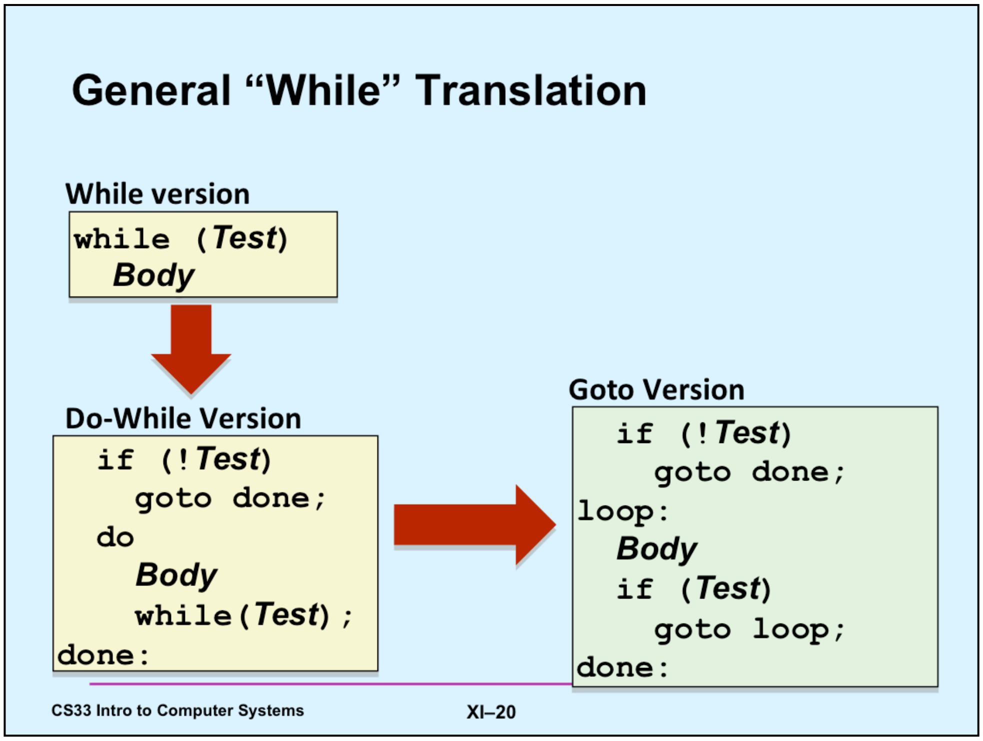
```
int pcount_while(unsigned x) {
  int result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Goto Version

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

- **Is this code equivalent to the do-while version?**
  - **must jump out of loop if test fails**

Supplied by CMU.



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“For” Loop Example

C Code

```
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

- **Is this code equivalent to other versions?**

Supplied by CMU.

“For” Loop Form

General Form

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

```
for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
}
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned mask = 1 << i;
  result += (x & mask) != 0;
}
```


Supplied by CMU.

“For” Loop → While Loop

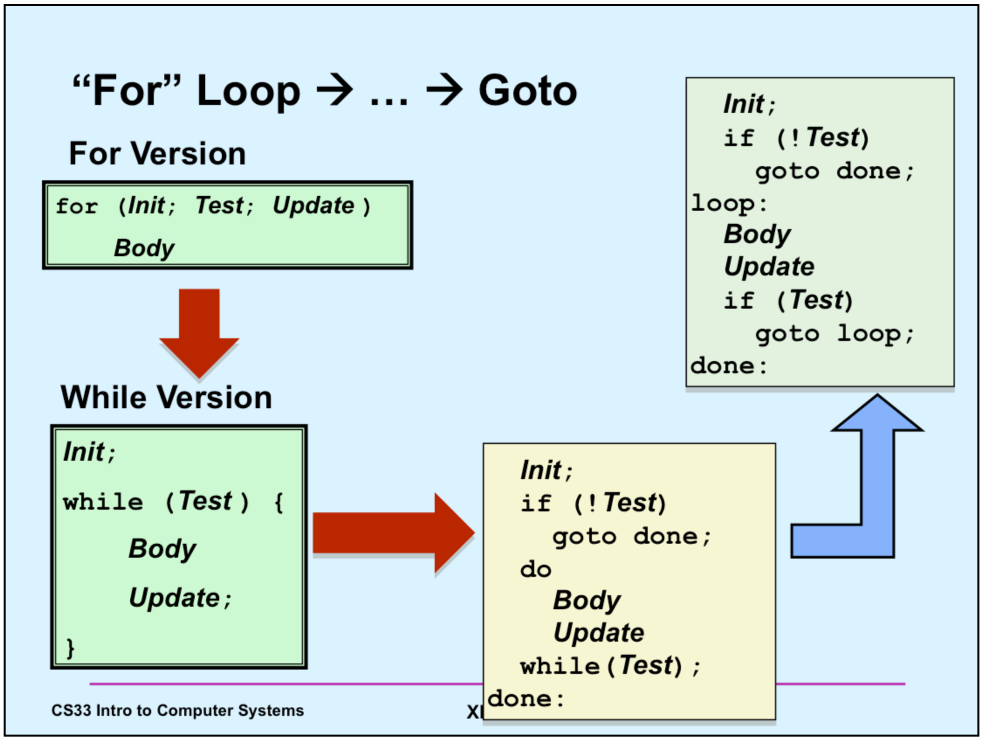
For Version

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

While Version

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


Supplied by CMU.



Supplied by CMU.

“For” Loop Conversion Example

C Code

```c
#define WSIZE 8*sizeof(int)
int pcount_for(unsigned x) {
  int i;
  int result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  return result;
}
```

Initial test can be optimized away

Goto Version

```c
int pcount_for_gt(unsigned x) {
  int i;
  int result = 0;
  i = 0;                        Init
  if (!(i < WSIZE))             !Test
    goto done;
 loop:                          Body
  {
    unsigned mask = 1 << i;
    result += (x & mask) != 0;
  }
  i++;  Update
  if (i < WSIZE)  Test
    goto loop;
 done:
  return result;
}
```

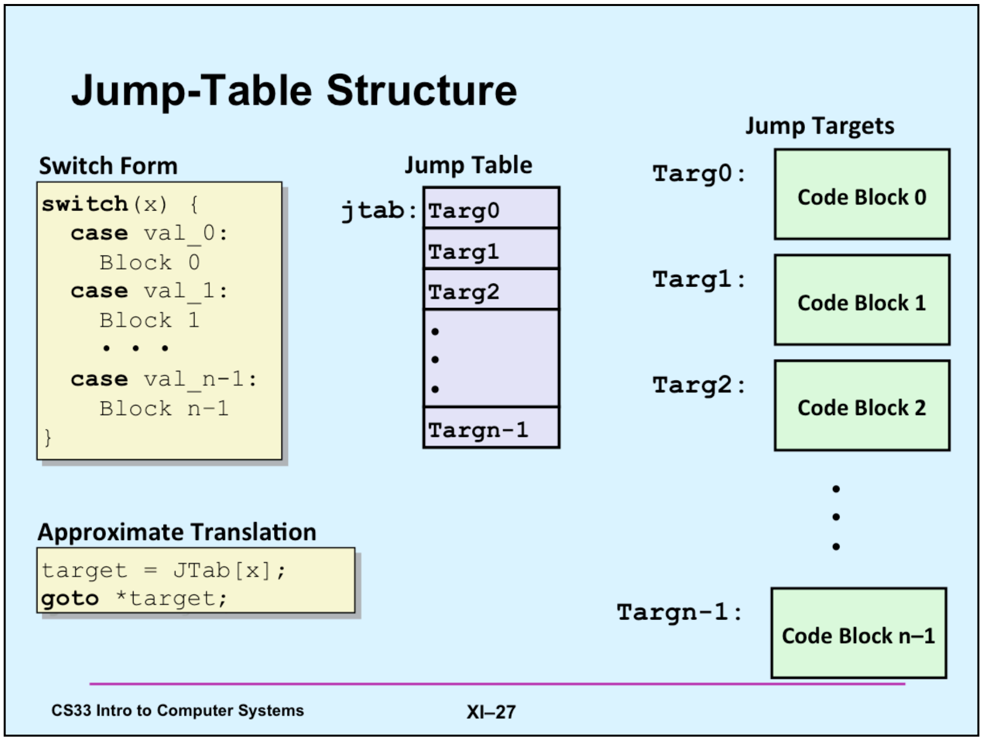

Supplied by CMU.

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

Supplied by CMU.



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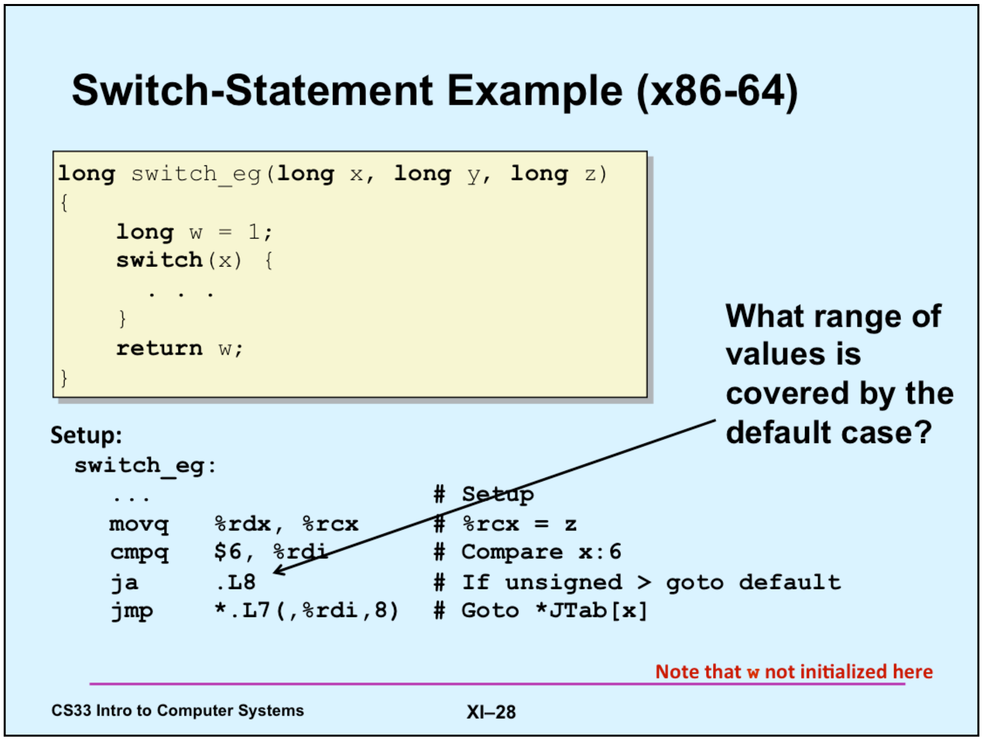


Supplied by CMU, but converted to x86-64.

Note that the *ja* in the slide causes a jump to occur if the previous comparison is interpreted as being performed on unsigned values, and the result is that x is greater than (above) 6. Given that x is declared to be a *signed* value, for what range of values of x will *ja* cause a jump to take place?

Note that the assembler code shown in the examples was produced by compiling the C code using gcc with the "-O1" flag.

Switch-Statement Example

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

Jump table

```
.section    .rodata
  .align 4
.L7:
  .quad     .L8 # x = 0
  .quad     .L3 # x = 1
  .quad     .L4 # x = 2
  .quad     .L9 # x = 3
  .quad     .L8 # x = 4
  .quad     .L6 # x = 5
  .quad     .L6 # x = 6
```

Setup:

```
    switch_eg:
      . . .                   # Setup
      movq    %rdx, %rcx      # %rcx = z
      cmpq    $6, %rdi        # Compare x:6
      ja      .L8             # If unsigned > goto default
      jmp     *.L7(,%rdi,8)   # Goto *JTab[x]
```

Indirect jump

Supplied by CMU, but converted to x86-64.

Assembly-Setup Explanation

- **Table structure**
  - each target requires 8 bytes
  - base address at `.L7`

- **Jumping**

  direct: `jmp .L8`
  - jump target is denoted by label `.L8`

  indirect: `jmp *.L7(,%rdi,8)`
  - start of jump table: `.L7`
  - must scale by factor of 8 (labels have 8 bytes on x86-64)
  - fetch target from effective address `.L7 + rdi*8`
    - » only for $0 \le x \le 6$

Jump table

```
.section   .rodata
  .align 4
.L7:
  .quad     .L8 # x = 0
  .quad     .L3 # x = 1
  .quad     .L4 # x = 2
  .quad     .L9 # x = 3
  .quad     .L8 # x = 4
  .quad     .L6 # x = 5
  .quad     .L6 # x = 6
```


Supplied by CMU, but converted to x86-64.

Jump Table

Jump table

```
.section   .rodata
  .align 4
.L7:
  .quad    .L8 # x = 0
  .quad    .L3 # x = 1
  .quad    .L4 # x = 2
  .quad    .L9 # x = 3
  .quad    .L8 # x = 4
  .quad    .L6 # x = 5
  .quad    .L6 # x = 6
```

```
switch(x) {
case 1:        // .L3
    w = y*z;
    break;
case 2:        // .L4
    w = y/z;
    /* Fall Through */
case 3:        // .L9
    w += z;
    break;
case 5:
case 6:        // .L6
    w -= z;
    break;
default:       // .L8
    w = 2;
}
```


Supplied by CMU, but converted to x86-64.

Code Blocks (Partial)

```
switch(x) {
case 1:       // .L3
      w = y*z;
      break;
 . . .
case 5:       // .L6
case 6:       // .L6
    w -= z;
    break;
default:      // .L8
    w = 2;
}
```

```
.L3:               # x == 1
  movl  %rsi, %rax  # y
  imulq %rdx, %rax  # w = y*z
  ret
.L6:               # x == 5, x == 6
  movl  $1, %eax # w = 1
  subq  %rdx, %rax  # w -= z
  ret
.L8:               # Default
  movl  $2, %eax # w = 2
  ret
```


Supplied by CMU, but converted to x86-64.

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;
```


Supplied by CMU, but converted to x86-64.

Code Blocks (Rest)

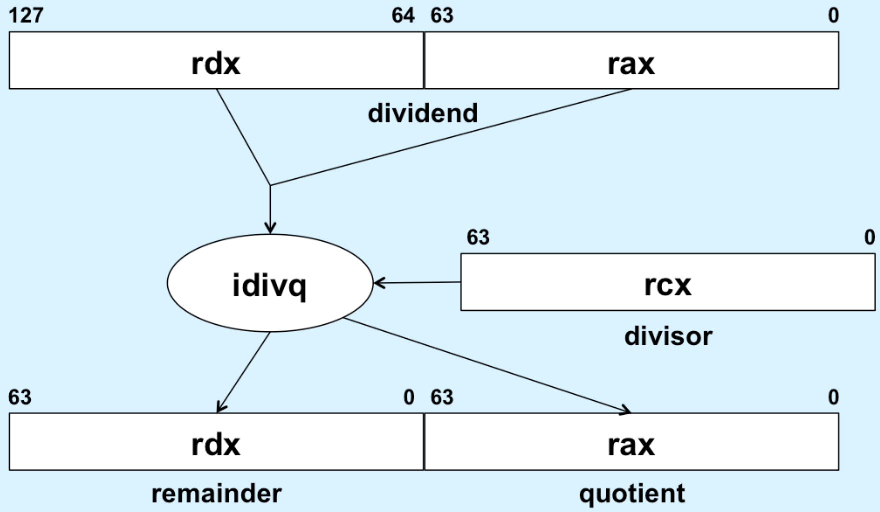
```
switch(x) {
   . . .
   case 2:  // .L4
       w = y/z;
       /* Fall Through */
   case 3:  // .L9
       w += z;
       break;
   . . .
}
```

```
.L4:                # x == 2
   movq  %rsi, %rax
   movq  %rsi, %rdx
   sarq  $63, %rdx
   idivq %rcx      # w = y/z
   jmp   .L5
.L9:     # x == 3
   movl  $1, %eax # w = 1
.L5:     # merge:
   addq  %rcx, %rax # w += z
   ret
```


Supplied by CMU, but converted to x86-64.

The code following the .L4 label requires some explanation. The *idivq* instruction is special in that it takes a 128-bit dividend that is implicitly assumed to reside in registers *rdx* and *rax*. Its single operand specifies the divisor. The quotient is always placed in the *rax* register, and the remainder in the *rdx* register. In our example, *y*, which we want to be the dividend, is copied into both the *rax* and *rdx* registers. The *sarq* (shift arithmetic right quadword) instruction propagates the sign bit of *rdx* across the entire register, replacing its original contents. Thus, if one considers *rdx* to contain the most-significant bits of the dividend and *rax* to contain the least-significant bits, the pair of registers now contains the 128-bit version of *y*. The *idivq* instruction computes the quotient from dividing this 128-bit value by the 64-bit value contained in register *rcx* (containing *z*). The quotient is stored register *rax* (implicitly) and the remainder is stored in register *rdx* (and is ignored in our example). This illustrated in the next slide.

idivq



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x86-64 Object Code

- **Setup**
  - **label `.L8` becomes address `0x4004e5`**
  - **label `.L7` becomes address `0x4005c0`**

Assembly code

```
switch_eg:
  . . .
  ja     .L8           # If unsigned > goto default
  jmp    *.L7(,%rdi,8) # Goto *JTab[x]
```

Disassembled object code

```
00000000004004ac <switch_eg>:
 . . .
 4004b3: 77 30                ja     4004e5 <switch_eg+0x39>
 4004b5: ff 24 fd c0 05 40 00 jmpq    *0x4005c0(,%rdi,8)
```


Supplied by CMU, but converted to x86-64.

Disassembly was accomplished using “objdump –d”. Note that the text enclosed in angle brackets (“<“, “>”) is essentially a comment, relating the address (4004e5) to a symbolic location (0x39 bytes after the beginning of *switch_eg*).

x86-64 Object Code (cont.)

- **Jump table**
  - doesn't show up in disassembled code
  - can inspect using gdb

```
gdb switch
(gdb) x/7xg 0x4005c0
```

  - » examine 7 hexadecimal format "giant" words (8-bytes each)
  - » use command "`help x`" to get format documentation

```
0x4005c0:       0x00000000004004e5      0x00000000004004bc
0x4005d0:       0x00000000004004c4      0x00000000004004d3
0x4005e0:       0x00000000004004e5      0x00000000004004dc
0x4005f0:       0x00000000004004dc
```


Supplied by CMU, but converted to x86-64. We assume that the switch_eg function was included in a program whose name is *switch*. Hence, gdb is invoked from the shell with the argument "switch".

x86-64 Object Code (cont.)

- **Deciphering jump table**

```
0x4005c0:    0x00000000004004e5    0x00000000004004bc
0x4005d0:    0x00000000004004c4    0x00000000004004d3
0x4005e0:    0x00000000004004e5    0x00000000004004dc
0x4005f0:    0x00000000004004dc
```

Address	Value	x
0x4005c0	0x4004e5	0
0x4005c8	0x4004bc	1
0x4005d0	0x4004c4	2
0x4005d8	0x4004d3	3
0x4005e0	0x4004e5	4
0x4005e8	0x4004dc	5
0x4005f0	0x4004dc	6

Supplied by CMU, but converted to x86-64.

Disassembled Targets

```
(gdb) disassemble 0x4004bc,0x4004eb
 Dump of assembler code from 0x4004bc to 0x4004eb
   0x00000000004004bc <switch_eg+16>:   mov    %rsi,%rax
   0x00000000004004bf <switch_eg+19>:   imul   %rdx,%rax
   0x00000000004004c3 <switch_eg+23>:   retq
   0x00000000004004c4 <switch_eg+24>:   mov    %rsi,%rax
   0x00000000004004c7 <switch_eg+27>:   mov    %rsi,%rdx
   0x00000000004004ca <switch_eg+30>:   sar    $0x3f,%rdx
   0x00000000004004ce <switch_eg+34>:   idiv   %rcx
   0x00000000004004d1 <switch_eg+37>:   jmp    0x4004d8 <switch_eg+44>
   0x00000000004004d3 <switch_eg+39>:   mov    $0x1,%eax
   0x00000000004004d8 <switch_eg+44>:   add    %rcx,%rax
   0x00000000004004db <switch_eg+47>:   retq
   0x00000000004004dc <switch_eg+48>:   mov    $0x1,%eax
   0x00000000004004e1 <switch_eg+53>:   sub    %rdx,%rax
   0x00000000004004e4 <switch_eg+56>:   retq
   0x00000000004004e5 <switch_eg+57>:   mov    $0x2,%eax
   0x00000000004004ea <switch_eg+62>:   retq
```


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Matching Disassembled Targets

Value	x
0x4004e5	0
0x4004bc	1
0x4004c4	2
0x4004d3	3
0x4004e5	4
0x4004dc	5
0x4004dc	6

```
0x00000000004004bc:   mov    %rsi,%rax
0x00000000004004bf:   imul   %rdx,%rax
0x00000000004004c3:   retq
0x00000000004004c4:   mov    %rsi,%rax
0x00000000004004c7:   mov    %rsi,%rdx
0x00000000004004ca:   sar    $0x3f,%rdx
0x00000000004004ce:   idiv   %rcx
0x00000000004004d1:   jmp    0x4004d8
0x00000000004004d3:   mov    $0x1,%eax
0x00000000004004d8:   add    %rcx,%rax
0x00000000004004db:   retq
0x00000000004004dc:   mov    $0x1,%eax
0x00000000004004e1:   sub    %rdx,%rax
0x00000000004004e4:   retq
0x00000000004004e5:   mov    $0x2,%eax
0x00000000004004ea:   retq
```


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