

15-213

“The course that gives CMU its Zip!”

Machine-Level Programming II: Control Flow Sept. 12, 2007

Topics

- Condition Codes
 - Setting
 - Testing
- Control Flow
 - If-then-else
 - Varieties of Loops
 - Switch Statements
- x86-64 features
 - conditional move
 - different loop implementation

Condition Codes

Single Bit Registers

CF Carry Flag

SF Sign Flag

ZF Zero Flag

OF Overflow Flag

Implicitly Set By Arithmetic Operations

`addl Src, Dest`

`addq Src, Dest`

C analog: $t = a + b$

($a = \text{Src}, b = \text{Dest}$)

- CF set if carry out from most significant bit

- Used to detect unsigned overflow

- ZF set if $t == 0$

- SF set if $t < 0$

- OF set if two's complement overflow

- ($a > 0 \ \&\& \ b > 0 \ \&\& \ t < 0$)

- || ($a < 0 \ \&\& \ b < 0 \ \&\& \ t \geq 0$)

Not set by `leaq`, `inc`, or `dec` instructions

Setting Condition Codes (cont.)

Explicit Setting by Compare Instruction

`cmpl Src2,Src1` `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`
- OF set if two's complement overflow
 - `(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`

Setting Condition Codes (cont.)

Explicit Setting by Test instruction

```
testl Src2,Src1
```

```
testq Src2,Src1
```

- Sets condition codes based on value of *Src1* & *Src2*
 - Useful to have one of the operands be a mask
- `testl b,a` like computing `a&b` without setting destination
- ZF set when `a&b == 0`
- SF set when `a&b < 0`

Reading Condition Codes

SetX Instructions

- Set single byte based on combinations of condition codes

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	$(SF \wedge OF) \mid ZF$	Less or Equal (Signed)
seta	$\sim CF \& \sim ZF$	Above (unsigned)
setb	CF	Below (unsigned)

Reading Condition Codes (Cont.)

SetX Instructions

- Set single byte based on combinations of condition codes
- One of 8 addressable byte registers
 - Embedded within first 4 integer registers
 - Does not alter remaining 3 bytes
 - Typically use `movzbl` to finish job

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

Body

```
movl 12(%ebp),%eax    # eax = y
cmpl %eax,8(%ebp)    # Compare x : y ←
setg %al              # al = x > y
movzbl %al,%eax      # Zero rest of %eax
```

%eax	%ah	%al
%edx	%dh	%dl
%ecx	%ch	%cl
%ebx	%bh	%bl
%esi		
%edi		
%esp		
%ebp		

Note
inverted
ordering!

Reading condition codes: x86-64

SetX Instructions

- Set single byte based on combinations of condition codes
 - Does not alter remaining 7 bytes

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

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

- x86-64 arguments
 - x in %rdi
 - y in %rsi

Body (same for both)

(32-bit instructions set high order 32 bits to 0)

```
xorl %eax, %eax    # eax = 0
cmpq %rsi, %rdi    # Compare x : y
setg %al           # al = x > y
```

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

Conditional Branch Example

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

```
absdiff:  
    pushl   %ebp  
    movl   %esp, %ebp  
    movl   8(%ebp), %edx  
    movl   12(%ebp), %eax  
    cmpl   %eax, %edx  
    jle   .L7  
    subl   %eax, %edx  
    movl   %edx, %eax  
.L8:  
    leave  
    ret  
.L7:  
    subl   %edx, %eax  
    jmp   .L8
```

Set Up

Body1

Finish

Body2

Conditional Branch Example (Cont.)

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

- C allows “goto” as means of transferring control
 - Closer to machine-level programming style
- Generally considered bad coding style

Body1

```
# x in %edx, y in %eax
cmpl    %eax, %edx    # Compare x:y
jle     .L7           # <= Goto Else
subl    %eax, %edx    # x-= y
movl    %edx, %eax    # result = x
.L8:    # Exit:
```

Body2

```
.L7:    # Else:
subl    %edx, %eax    # result = y-x
jmp     .L8           # Goto Exit
```

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;  
Done:  
. . .  
Else:  
val = Else-Expr;  
goto 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

Conditionals: x86-64

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

```
absdiff: # x in %edi, y in %esi  
    movl    %edi, %eax    # v = x  
    movl    %esi, %edx    # ve = y  
    subl    %esi, %eax    # v -= y  
    subl    %edi, %edx    # ve -= x  
    cmpl    %esi, %edi    # x:y  
    cmovle  %edx, %eax    # v=ve if <=  
    ret
```

■ Conditional move instruction

- `cmovC src, dest`
- Move value from `src` to `dest` if condition `C` holds
- More efficient than conditional branching
 - » Simple & predictable control flow

General Form with Conditional Move

C Code

```
val = Test ? Then-Expr ? Else-Expr;
```

- Both values get computed
- Overwrite then-value with else-value if condition doesn't hold

Conditional Move Version

```
val = Then-Expr;  
vale = Else-Expr;  
val = vale if !Test;
```

Limitations of Conditional Move

```
val = Then-Expr;  
vale = Else-Expr;  
val = vale if !Test;
```

```
int xgty = 0, xltey = 0;  
  
int absdiff_se(  
    int x, int y)  
{  
    int result;  
    if (x > y) {  
        xgty++; result = x-y;  
    } else {  
        xltey++; result = y-x;  
    }  
    return result;  
}
```

Don't use when:

- Then-Expr or Else-Expr has side effect
- Then-Expr or Else-Expr requires significant computation

Implementing Loops

IA32

- All loops translated into form based on “do-while”

x86-64

- Also make use of “jump to middle”

Why the Difference

- IA32 compiler developed for machine where all operations costly
- x86-64 compiler developed for machine where unconditional branches incur (almost) no overhead

“Do-While” Loop Example

C Code

```
int fact_do(int x)
{
    int result = 1;
    do {
        result *= x;
        x = x-1;
    } while (x > 1);

    return result;
}
```

Goto Version

```
int fact_goto(int x)
{
    int result = 1;
loop:
    result *= x;
    x = x-1;
    if (x > 1)
        goto loop;
    return result;
}
```

- Use backward branch to continue looping
- Only take branch when “while” condition holds

“Do-While” Loop Compilation

Registers

%edx x

%eax result

Goto Version

```
int
fact_goto(int x)
{
    int result = 1;

loop:
    result *= x;
    x = x-1;
    if (x > 1)
        goto loop;

    return result;
}
```

Assembly

```
fact_goto:
    pushl %ebp                # Setup
    movl %esp,%ebp          # Setup
    movl $1,%eax            # eax = 1
    movl 8(%ebp),%edx       # edx = x

L11:
    imull %edx,%eax         # result *= x
    decl %edx               # x--
    cmpl $1,%edx           # Compare x : 1
    jg L11                  # if > goto loop

    movl %ebp,%esp         # Finish
    popl %ebp              # Finish
    ret                    # Finish
```

General “Do-While” Translation

C Code

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

Goto Version

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

- *Body* can be any C statement
 - Typically compound statement:

```
{  
  Statement1;  
  Statement2;  
  ...  
  Statementn;  
}
```

- *Test* is expression returning integer
 - = 0 interpreted as false ≠0 interpreted as true

“While” Loop Example #1

C Code

```
int fact_while(int x)
{
    int result = 1;
    while (x > 1) {

        result *= x;
        x = x-1;
    };

    return result;
}
```

First Goto Version

```
int fact_while_goto(int x)
{
    int result = 1;
loop:
    if (!(x > 1))
        goto done;
    result *= x;
    x = x-1;
    goto loop;
done:
    return result;
}
```

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

Alternative “While” Loop Translation

C Code

```
int fact_while(int x)
{
    int result = 1;
    while (x > 1) {
        result *= x;
        x = x-1;
    };
    return result;
}
```

- Historically used by GCC
- Uses same inner loop as do-while version
- Guards loop entry with extra test

Second Goto Version

```
int fact_while_goto2(int x)
{
    int result = 1;
    if (!(x > 1))
        goto done;
loop:
    result *= x;
    x = x-1;
    if (x > 1)
        goto loop;
done:
    return result;
}
```

General “While” Translation

C Code

```
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:
```

New Style “While” Loop Translation

C Code

```
int fact_while(int x)
{
    int result = 1;
    while (x > 1) {
        result *= x;
        x = x-1;
    };
    return result;
}
```

Goto Version

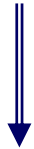
```
int fact_while_goto3(int x)
{
    int result = 1;
    goto middle;
loop:
    result *= x;
    x = x-1;
middle:
    if (x > 1)
        goto loop;
    return result;
}
```

- Recent technique for GCC
 - Both IA32 & x86-64
- First iteration jumps over body computation within loop

Jump-to-Middle While Translation

C Code

```
while (Test)  
    Body
```



Goto Version

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

- Avoids duplicating test code
- Unconditional `goto` incurs no performance penalty
- `for` loops compiled in similar fashion

Jump-to-Middle Example

```
int fact_while(int x)
{
    int result = 1;
    while (x > 1) {
        result *= x;
        x--;
    };
    return result;
}
```

- Most common strategy for recent IA32 & x86-64 code generation

```
# x in %edx, result in %eax
    jmp     L34          # goto Middle
L35:          # Loop:
    imull  %edx, %eax   # result *= x
    decl   %edx         # x--
L34:          # Middle:
    cmpl   $1, %edx    # x:1
    jg     L35          # if >, goto Loop
```


“For” Loop Example

```
/* Compute x raised to nonnegative power p */
int
ipwr_for(int x, unsigned p)
{
    int result;
    for (result = 1; p != 0; p = p>>1) {
        if (p & 0x1)
            result *= x;
        x = x*x;
    }
    return result;
}
```

Algorithm

- Exploit property that $p = p_0 + 2p_1 + 4p_2 + \dots + 2^{n-1}p_{n-1}$
- Gives: $x^p = z_0 \cdot z_1^2 \cdot (z_2^2)^2 \cdot \dots \cdot \underbrace{(\dots((z_{n-1}^2)^2)\dots)^2}_{n-1 \text{ times}}$
 - $z_i = 1$ when $p_i = 0$
 - $z_i = x$ when $p_i = 1$
- Complexity $O(\log p)$

Example

$$3^{10} = 3^2 * 3^8$$

$$= 3^2 * ((3^2)^2)^2$$

ipwr Computation

```
/* Compute x raised to nonnegative power p */
int
ipwr_for(int x, unsigned p)
{
    int result;
    for (result = 1; p != 0; p = p>>1) {
        if (p & 0x1)
            result *= x;
        x = x*x;
    }
    return result;
}
```

result	x	p
1	3	10
1	9	5
9	81	2
9	6561	1
531441	43046721	0

“For” Loop Example

```
int result;  
for (result = 1;  
     p != 0;  
     p = p>>1)  
{  
    if (p & 0x1)  
        result *= x;  
    x = x*x;  
}
```

General Form

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

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
{  
    if (p & 0x1)  
        result *= x;  
    x = x*x;  
}
```

“For” → “While” → “Do-While”

For Version

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

While Version

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

Do-While Version

```
Init;  
if (!Test)  
  goto done;  
do {  
  Body  
  Update ;  
} while (Test)  
done:
```

Goto Version

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

“For” Loop Compilation #1

Goto Version

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



```
result = 1;  
if (p == 0)  
    goto done;  
loop:  
    if (p & 0x1)  
        result *= x;  
    x = x*x;  
    p = p >> 1;  
    if (p != 0)  
        goto loop;  
done:
```

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
{  
    if (p & 0x1)  
        result *= x;  
    x = x*x;  
}
```

“For” → “While” (Jump-to-Middle)

For Version

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

While Version

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

Goto Version

```
Init;  
goto middle;  
loop:  
    Body  
    Update ;  
middle:  
    if ( Test )  
        goto loop;  
done:
```

“For” Loop Compilation #2

Goto Version

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



```
result = 1;  
goto middle;  
loop:  
    if (p & 0x1)  
        result *= x;  
    x = x*x;  
    p = p >> 1;  
middle:  
    if (p != 0)  
        goto loop;  
done:
```

Init

```
result = 1
```

Test

```
p != 0
```

Update

```
p = p >> 1
```

Body

```
{  
    if (p & 0x1)  
        result *= x;  
    x = x*x;  
}
```

Switch Statements

Implementation Options

- Series of conditionals
 - Organize in tree structure
 - Logarithmic performance
- Jump Table
 - Lookup branch target
 - Constant time
 - Possible when cases are small integer constants
- GCC
 - Picks one based on case structure

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;
}
```

Features

- Multiple case labels
- Fall through cases
- Missing cases

Jump Table Structure

Switch Form

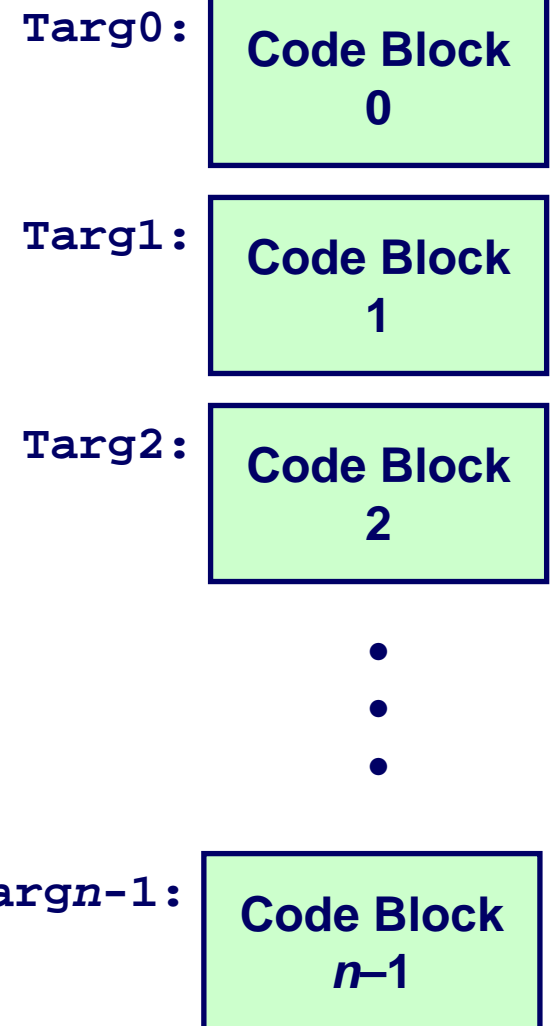
```
switch(x) {  
  case val_0:  
    Block 0  
  case val_1:  
    Block 1  
    . . .  
  case val_n-1:  
    Block n-1  
}
```

Jump Table

jtab:

Targ0
Targ1
Targ2
• • •
Targn-1

Jump Targets



Approx. Translation

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

Switch Statement Example (IA32)

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

Setup:

```
switch_eg:
    pushl %ebp                # Setup
    movl  %esp, %ebp         # Setup
    pushl %ebx               # Setup
    movl  $1, %ebx           # w = 1
    movl  8(%ebp), %edx       # edx = x
    movl  16(%ebp), %ecx      # ecx = z
    cmpl  $6, %edx           # x:6
    ja   .L61                # if > goto default
    jmp  *.L62(,%edx,4)       # goto JTab[x]
```

Assembly Setup Explanation

Table Structure

- Each target requires 4 bytes
- Base address at `.L62`

Jumping

```
jmp .L61
```

- Jump target is denoted by label `.L61`

```
jmp *.L62(,%edx,4)
```

- Start of jump table denoted by label `.L62`
- Register `%edx` holds `x`
- Must scale by factor of 4 to get offset into table
- Fetch target from effective Address `.L61 + x*4`
 - Only for $0 \leq x \leq 6$

Jump Table

Table Contents

```
.section .rodata
```

```
.align 4
```

```
.L62:
```

```
.long .L61 # x = 0
```

```
.long .L56 # x = 1
```

```
.long .L57 # x = 2
```

```
.long .L58 # x = 3
```

```
.long .L61 # x = 4
```

```
.long .L60 # x = 5
```

```
.long .L60 # x = 6
```

```
switch(x) {
```

```
case 1: // .L56
```

```
    w = y*z;
```

```
    break;
```

```
case 2: // .L57
```

```
    w = y/z;
```

```
    /* Fall Through */
```

```
case 3: // .L58
```

```
    w += z;
```

```
    break;
```

```
case 5:
```

```
case 6: // .L60
```

```
    w -= z;
```

```
    break;
```

```
default: // .L61
```

```
    w = 2;
```

```
}
```

Code Blocks (Partial)

```
switch(x) {
    . . .
case 2:      // .L57
    w = y/z;
    /* Fall Through */
case 3:      // .L58
    w += z;
    break;
    . . .
default:    // .L61
    w = 2;
}
```

```
.L61: // Default case
    movl    $2, %ebx      # w = 2
    movl    %ebx, %eax   # Return w
    popl    %ebx
    leave
    ret
.L57: // Case 2:
    movl    12(%ebp), %eax # y
    cltd
    idivl   %ecx          # y/z
    movl    %eax, %ebx   # w = y/z
# Fall through
.L58: // Case 3:
    addl    %ecx, %ebx   # w+= z
    movl    %ebx, %eax   # Return w
    popl    %ebx
    leave
    ret
```

Code Blocks (Rest)

```
switch(x) {  
  case 1:      // .L56  
    w = y*z;  
    break;  
    . . .  
  case 5:  
  case 6:      // .L60  
    w -= z;  
    break;  
    . . .  
}
```

```
.L60: // Cases 5&6:  
  subl  %ecx, %ebx  # w -= z  
  movl  %ebx, %eax  # Return w  
  popl  %ebx  
  leave  
  ret  
.L56: // Case 1:  
  movl  12(%ebp), %ebx # w = y  
  imull %ecx, %ebx    # w*= z  
  movl  %ebx, %eax   # Return w  
  popl  %ebx  
  leave  
  ret
```

x86-64 Switch Implementation

- Same general idea, adapted to 64-bit code
- Table entries 64 bits (pointers)
- Cases use revised code

Jump Table

```
.section .rodata
    .align 8
.L62:
    .quad    .L55    # x = 0
    .quad    .L50    # x = 1
    .quad    .L51    # x = 2
    .quad    .L52    # x = 3
    .quad    .L55    # x = 4
    .quad    .L54    # x = 5
    .quad    .L54    # x = 6
```

```
switch(x) {
case 1:      // .L50
    w = y*z;
    break;
    . . .
}
```

```
.L50: // Case 1:
    movq    %rsi, %r8    # w = y
    imulq   %rdx, %r8    # w *= z
    movq    %r8, %rax    # Return w
    ret
```


IA32 Object Code

Setup

- Label `.L61` becomes address `0x8048630`
- Label `.L62` becomes address `0x80488dc`

Assembly Code

```
switch_eg:
    . . .
    ja     .L61          # if > goto default
    jmp    *.L62(, %edx, 4) # goto JTab[x]
```

Disassembled Object Code

```
08048610 <switch_eg>:
    . . .
    8048622: 77 0c          ja     8048630
    8048624: ff 24 95 dc 88 04 08 jmp    *0x80488dc(, %edx, 4)
```

IA32 Object Code (cont.)

Jump Table

- Doesn't show up in disassembled code
- Can inspect using GDB

```
gdb asm-cnt1
```

```
(gdb) x/7xw 0x80488dc
```

- Examine 7 hexadecimal format “words” (4-bytes each)
- Use command “help x” to get format documentation

```
0x80488dc:
```

```
0x08048630
```

```
0x08048650
```

```
0x0804863a
```

```
0x08048642
```

```
0x08048630
```

```
0x08048649
```

```
0x08048649
```

Disassembled Targets

```
8048630:      bb 02 00 00 00      mov     $0x2,%ebx
8048635:      89 d8              mov     %ebx,%eax
8048637:      5b                pop     %ebx
8048638:      c9                leave
8048639:      c3                ret
804863a:      8b 45 0c          mov     0xc(%ebp),%eax
804863d:      99                cld
804863e:      f7 f9            idiv   %ecx
8048640:      89 c3              mov     %eax,%ebx
8048642:      01 cb            add     %ecx,%ebx
8048644:      89 d8              mov     %ebx,%eax
8048646:      5b                pop     %ebx
8048647:      c9                leave
8048648:      c3                ret
8048649:      29 cb            sub     %ecx,%ebx
804864b:      89 d8              mov     %ebx,%eax
804864d:      5b                pop     %ebx
804864e:      c9                leave
804864f:      c3                ret
8048650:      8b 5d 0c          mov     0xc(%ebp),%ebx
8048653:      0f af d9          imul  %ecx,%ebx
8048656:      89 d8              mov     %ebx,%eax
8048658:      5b                pop     %ebx
8048659:      c9                leave
804865a:      c3                ret
```

Matching Disassembled Targets

0x08048630

0x08048650

0x0804863a

0x08048642

0x08048630

0x08048649

0x08048649

8048630:	bb 02 00 00 00	mov
8048635:	89 d8	mov
8048637:	5b	pop
8048638:	c9	leave
8048639:	c3	ret
804863a:	8b 45 0c	mov
804863d:	99	cld
804863e:	f7 f9	idiv
8048640:	89 c3	mov
8048642:	01 cb	add
8048644:	89 d8	mov
8048646:	5b	pop
8048647:	c9	leave
8048648:	c3	ret
8048649:	29 cb	sub
804864b:	89 d8	mov
804864d:	5b	pop
804864e:	c9	leave
804864f:	c3	ret
8048650:	8b 5d 0c	mov
8048653:	0f af d9	imul
8048656:	89 d8	mov
8048658:	5b	pop
8048659:	c9	leave
804865a:	c3	ret

x86-64 Object Code

Setup

- Label `.L61` becomes address `0x0000000000400716`
- Label `.L62` becomes address `0x0000000000400990`

Assembly Code

```
switch_eg:
    . . .
    ja     .L55          # if > goto default
    jmp   *.L56(,%rdi,8) # goto JTab[x]
```

Disassembled Object Code

```
0000000000400700 <switch_eg>:
    . . .
    40070d: 77 07          ja     400716
    40070f: ff 24 fd 90 09 40 00 jmpq   *0x400990(,%rdi,8)
```

x86-64 Object Code (cont.)

Jump Table

- Can inspect using GDB

```
gdb asm-cnt1
```

```
(gdb) x/7xg 0x400990
```

- Examine 7 hexadecimal format “giant words” (8-bytes each)
- Use command “help x” to get format documentation

```
0x400990:
```

```
0x00000000000400716
```

```
0x00000000000400739
```

```
0x00000000000400720
```

```
0x0000000000040072b
```

```
0x00000000000400716
```

```
0x00000000000400732
```

```
0x00000000000400732
```

Sparse Switch Example

```
/* Return x/111 if x is multiple
   && <= 999.  -1 otherwise */
int div111(int x)
{
    switch(x) {
    case 0: return 0;
    case 111: return 1;
    case 222: return 2;
    case 333: return 3;
    case 444: return 4;
    case 555: return 5;
    case 666: return 6;
    case 777: return 7;
    case 888: return 8;
    case 999: return 9;
    default: return -1;
    }
}
```

- Not practical to use jump table
 - Would require 1000 entries
- Obvious translation into if-then-else would have max. of 9 tests

Sparse Switch Code (IA32)

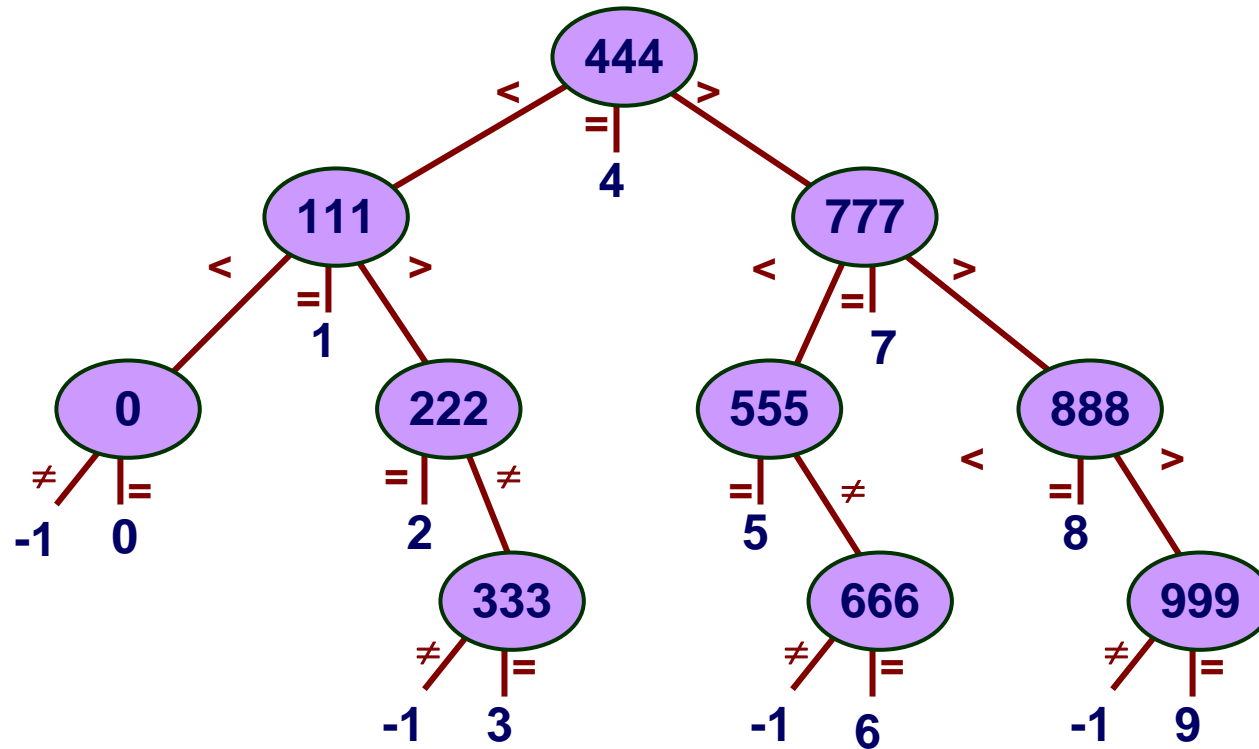
```
movl 8(%ebp),%eax # get x
cmpl $444,%eax    # x:444
je L8
jg L16
cmpl $111,%eax    # x:111
je L5
jg L17
testl %eax,%eax   # x:0
je L4
jmp L14

. . .
```

- Compares x to possible case values
- Jumps different places depending on outcomes

```
. . .
L5:
    movl $1,%eax
    jmp L19
L6:
    movl $2,%eax
    jmp L19
L7:
    movl $3,%eax
    jmp L19
L8:
    movl $4,%eax
    jmp L19
. . .
```


Sparse Switch Code Structure



- Organizes cases as binary tree
- Logarithmic performance

Summarizing

C Control

- if-then-else
- do-while
- while, for
- switch

Assembler Control

- Conditional jump
- Conditional move
- Indirect jump

Compiler

- Must generate assembly code to implement more complex control

Standard Techniques

- IA32 loops converted to do-while form
- x86-64 loops use jump-to-middle
- Large switch statements use jump tables

Conditions in CISC

- CISC machines generally have condition code registers