15-213

"The course that gives CMU its Zip!"

Machine-Level Programming II: Control Flow
Sept. 11, 2003

Topics

- Condition Codes
  - Setting
  - Testing
- Control Flow
  - If-then-else
  - Varieties of Loops
  - Switch Statements

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*

C analog: `t = a + b`

- 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>=0)`

Not Set by `leal` instruction

Setting Condition Codes (cont.)

Explicit Setting by Compare Instruction

`cmpl` *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***

- 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

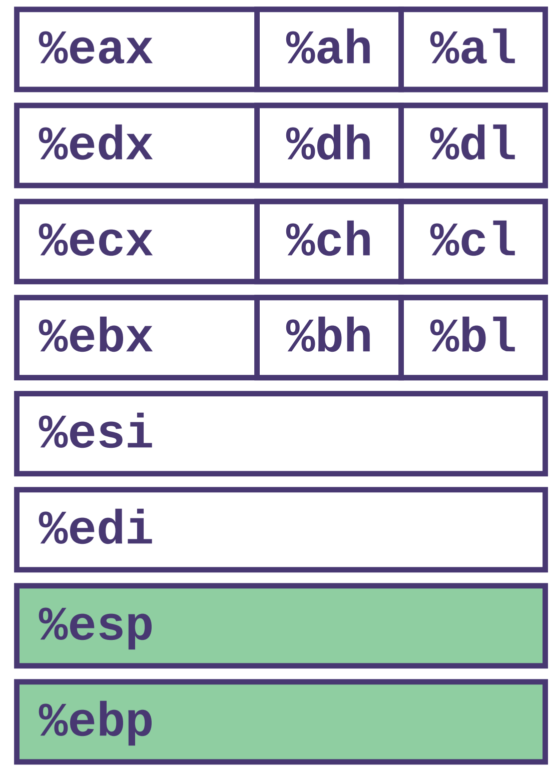
- Set single byte based on combinations of condition codes

SetX	Condition	Description
`sete`	`ZF`	Equal / Zero
`setne`	`~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)

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
```

Note inverted ordering!

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

```
int max(int x, int y)
{
  if (x > y)
    return x;
  else
    return y;
}
```

```
_max:
        pushl %ebp              } Set
        movl %esp,%ebp          } Up

        movl 8(%ebp),%edx       }
        movl 12(%ebp),%eax      }
        cmpl %eax,%edx          } Body
        jle L9                  }
        movl %edx,%eax          }
L9:

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

Conditional Branch Example (Cont.)

```
int goto_max(int x, int y)
{
  int rval = y;
  int ok = (x <= y);
  if (ok)
    goto done;
  rval = x;
done:
  return rval;
}
```

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

```
    movl 8(%ebp),%edx    # edx = x
    movl 12(%ebp),%eax   # eax = y
    cmpl %eax,%edx       # x : y
    jle L9               # if x <= y goto L9
    movl %edx,%eax       # eax = x   } Skipped when x ≤ y
L9:                      # Done:
```

"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

Goto Version

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

Registers

```
%edx   x
%eax   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**

Actual "While" Loop Translation

C Code

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

- 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:
```

"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** $p = p_0 + 2p_1 + 4p_2 + \ldots 2^{n-1}p_{n-1}$
- **Gives:** $x^p = z_0 \cdot z_1^{\ 2} \cdot (z_2^{\ 2})^{\ 2} \cdot \ldots \cdot (\ldots((z_{n-1}^{\ 2})^{\ 2})\ldots)^{\ 2}$ — $\underbrace{\qquad}_{n-1 \text{ times}}$

  $z_i = 1$ 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	*Test*	*Update*
`result = 1`	`p != 0`	`p = p >> 1`

Body

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

"For" → "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

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;
}
```

Switch Statements

```
typedef enum
 {ADD, MULT, MINUS, DIV, MOD, BAD}
    op_type;

char unparse_symbol(op_type op)
{
  switch (op) {
  case ADD :
    return '+';
  case MULT:
    return '*';
  case MINUS:
    return '-';
  case DIV:
    return '/';
  case MOD:
    return '%';
  case BAD:
    return '?';
  }
}
```

Implementation Options

- Series of conditionals
  - Good if few cases
  - Slow if many
- Jump Table
  - Lookup branch target
  - Avoids conditionals
  - Possible when cases are small integer constants
- GCC
  - Picks one based on case structure
- Bug in example code
  - No default given

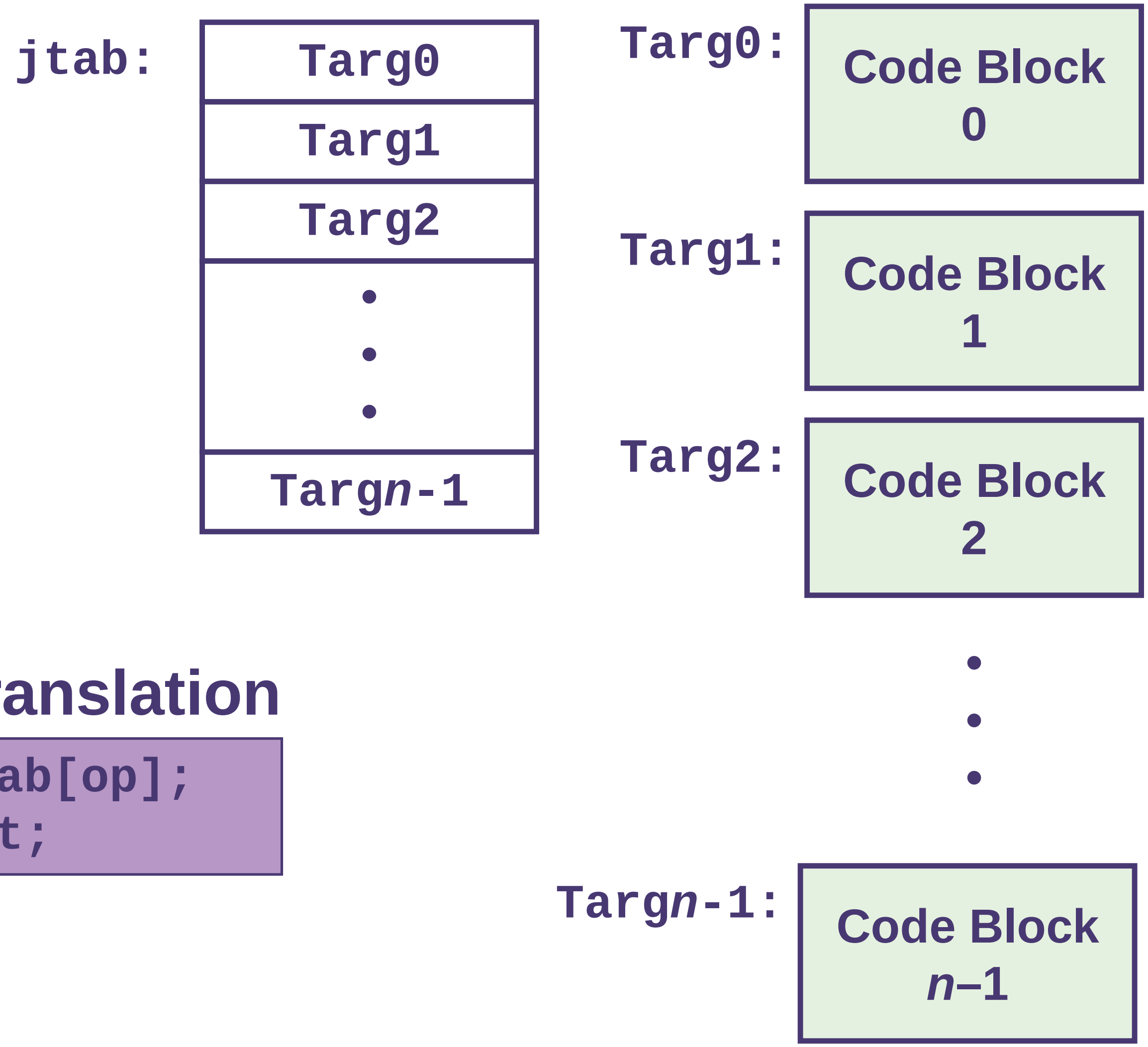
Jump Table Structure

Switch Form

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

Jump Table

Jump Targets



Approx. Translation

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

Switch Statement Example

Branching Possibilities

```
typedef enum
  {ADD, MULT, MINUS, DIV, MOD, BAD}
    op_type;

char unparse_symbol(op_type op)
{
  switch (op) {
    • • •
  }
}
```

Enumerated Values

```
ADD    0
MULT   1
MINUS  2
DIV    3
MOD    4
BAD    5
```

Setup:

```
unparse_symbol:
  pushl %ebp              # Setup
  movl %esp,%ebp          # Setup
  movl 8(%ebp),%eax       # eax = op
  cmpl $5,%eax            # Compare op : 5
  ja .L49                 # If > goto done
  jmp *.L57(,%eax,4)      # goto Table[op]
```

Assembly Setup Explanation

Symbolic Labels

- **Labels of form `.L`*XX* translated into addresses by assembler**

Table Structure

- **Each target requires 4 bytes**
- **Base address at `.L57`**

Jumping

```
jmp .L49
```

- Jump target is denoted by label **`.L49`**

```
jmp *.L57(,%eax,4)
```

- Start of jump table denoted by label **`.L57`**
- Register **`%eax`** holds **`op`**
- Must scale by factor of 4 to get offset into table
- Fetch target from effective Address **`.L57 + op*4`**

Jump Table

Table Contents

```
.section .rodata
   .align 4
.L57:
  .long .L51 #Op = 0
  .long .L52 #Op = 1
  .long .L53 #Op = 2
  .long .L54 #Op = 3
  .long .L55 #Op = 4
  .long .L56 #Op = 5
```

Enumerated Values

```
ADD     0
MULT    1
MINUS   2
DIV     3
MOD     4
BAD     5
```

Targets & Completion

```
.L51:
    movl $43,%eax # '+'
    jmp .L49
.L52:
    movl $42,%eax # '*'
    jmp .L49
.L53:
    movl $45,%eax # '-'
    jmp .L49
.L54:
    movl $47,%eax # '/'
    jmp .L49
.L55:
    movl $37,%eax # '%'
    jmp .L49
.L56:
    movl $63,%eax # '?'
    # Fall Through to .L49
```

Switch Statement Completion

```
.L49:                           # Done:
    movl %ebp,%esp              # Finish
    popl %ebp                   # Finish
    ret                         # Finish
```

Puzzle

- What value returned when op is invalid?

Answer

- Register `%eax` set to op at beginning of procedure
- This becomes the returned value

Advantage of Jump Table

- Can do *k*-way branch in *O*(1) operations

Object Code

Setup

- Label `.L49` becomes address `0x804875c`
- Label `.L57` becomes address `0x8048bc0`

```
08048718 <unparse_symbol>:
8048718:55                pushl  %ebp
8048719:89 e5             movl   %esp,%ebp
804871b:8b 45 08          movl   0x8(%ebp),%eax
804871e:83 f8 05          cmpl   $0x5,%eax
8048721:77 39             ja     804875c <unparse_symbol+0x44>
8048723:ff 24 85 c0 8b jmp    *0x8048bc0(,%eax,4)
```

Object Code (cont.)

Jump Table

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

```
gdb code-examples
(gdb) x/6xw 0x8048bc0
```

  - Examine 6 hexadecimal format "words" (4-bytes each)
  - Use command "`help x`" to get format documentation

```
0x8048bc0 <_fini+32>:
  0x08048730
  0x08048737
  0x08048740
  0x08048747
  0x08048750
  0x08048757
```

Extracting Jump Table from Binary

Jump Table Stored in Read Only Data Segment (.rodata)

- Various fixed values needed by your code

Can examine with objdump

`objdump code-examples –s --section=.rodata`

- Show everything in indicated segment.

Hard to read

- Jump table entries shown with reversed byte ordering

```
Contents of section .rodata:
 8048bc0 30870408 37870408 40870408 47870408  0...7...@...G...
 8048bd0 50870408 57870408 46616374 28256429  P...W...Fact(%d)
 8048be0 203d2025 6c640a00 43686172 203d2025   = %ld..Char = %
 …
```

- E.g., **`30870408`** really means **`0x08048730`**

Disassembled Targets

```
8048730: b8 2b 00 00 00    movl   $0x2b,%eax
8048735: eb 25             jmp    804875c <unparse_symbol+0x44>
8048737: b8 2a 00 00 00    movl   $0x2a,%eax
804873c: eb 1e             jmp    804875c <unparse_symbol+0x44>
804873e: 89 f6             movl   %esi,%esi
8048740: b8 2d 00 00 00    movl   $0x2d,%eax
8048745: eb 15             jmp    804875c <unparse_symbol+0x44>
8048747: b8 2f 00 00 00    movl   $0x2f,%eax
804874c: eb 0e             jmp    804875c <unparse_symbol+0x44>
804874e: 89 f6             movl   %esi,%esi
8048750: b8 25 00 00 00    movl   $0x25,%eax
8048755: eb 05             jmp    804875c <unparse_symbol+0x44>
8048757: b8 3f 00 00 00    movl   $0x3f,%eax
```

- `movl %esi,%esi` does nothing
- Inserted to align instructions for better cache performance

Matching Disassembled Targets

Entry

`0x08048730`
`0x08048737`
`0x08048740`
`0x08048747`
`0x08048750`
`0x08048757`

```
8048730: b8 2b 00 00 00     movl
8048735: eb 25              jmp
8048737: b8 2a 00 00 00     movl
804873c: eb 1e              jmp
804873e: 89 f6              movl
8048740: b8 2d 00 00 00     movl
8048745: eb 15              jmp
8048747: b8 2f 00 00 00     movl
804874c: eb 0e              jmp
804874e: 89 f6              movl
8048750: b8 25 00 00 00     movl
8048755: eb 05              jmp
8048757: b8 3f 00 00 00     movl
```

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

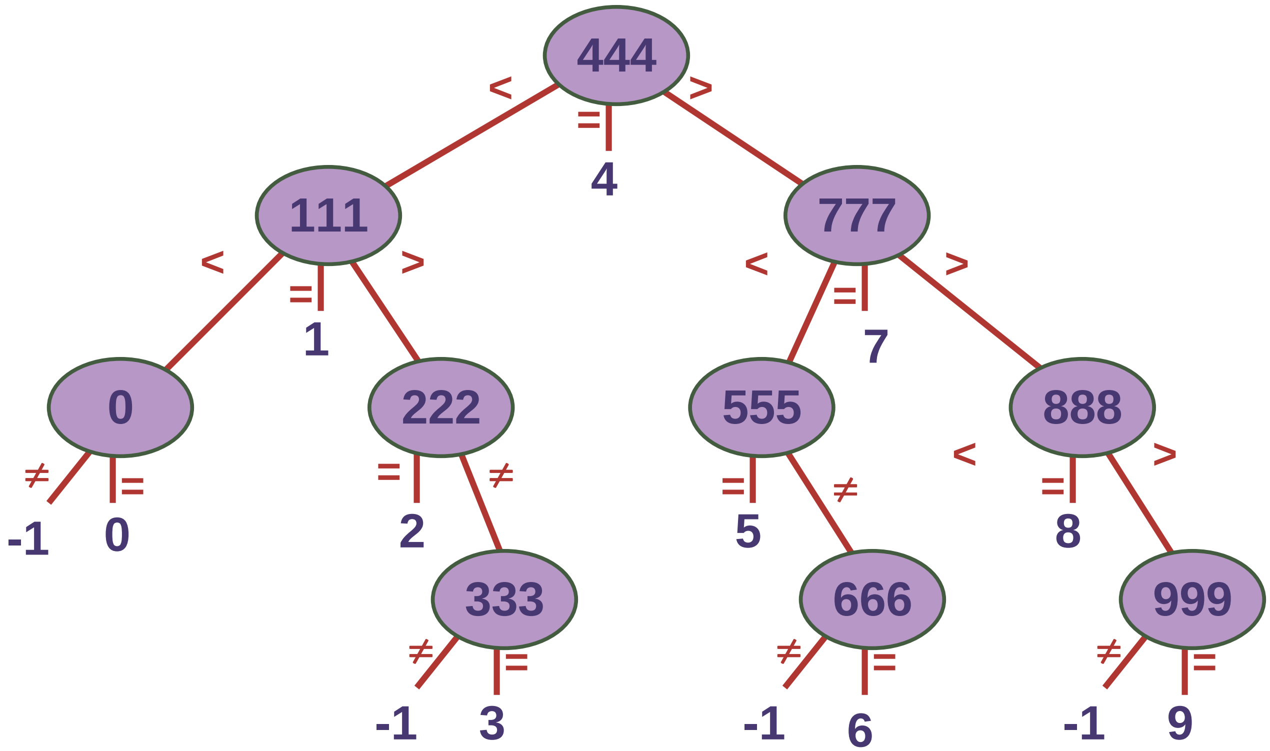
```
    movl 8(%ebp),%eax  # get x
    cmpl $444,%eax     # x:444
    je L8
    jg L16
    cmpl $111,%eax     # x:111
    je L5
    jg L17
    testl %eax,%eax    # x:0
    je L4
    jmp L14

    . . .
```

- 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
- switch

Assembler Control

- jump
- Conditional jump

Compiler

- Must generate assembly code to implement more complex control

Standard Techniques

- All loops converted to do-while form
- Large switch statements use jump tables

Conditions in CISC

- CISC machines generally have condition code registers

Conditions in RISC

- Use general registers to store condition information
- Special comparison instructions
- E.g., on Alpha:

```
cmple $16,1,$1
```

  - Sets register $1 to 1 when Register $16 <= 1