# 15-213

*"The course that gives CMU its Zip!"*

# Machine-Level Programming II: Control Flow Sept. 12, 2002

## Topics

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

`class06.ppt`

# 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

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

```
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 Up
        movl %esp,%ebp

        movl 8(%ebp),%edx
        movl 12(%ebp),%eax      } Body
        cmpl %eax,%edx
        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 <= goto L9
    movl %edx,%eax       # eax = x
L9:                      # Done:
```

Skipped when $x \le y$



# "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: $x^p = z_0 \cdot z_1^{\,2} \cdot (z_2^{\,2})^{2} \cdot \ldots \cdot \underbrace{(\ldots((z_{n-1}^{\,2})^{2})\ldots)^{2}}_{n-1 \text{ times}}$
  - $z_i = 1$ 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"

**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

```
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
```

### 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 `.LXX` 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
```

  - E<u>x</u>amine <u>6</u> he<u>x</u>adecimal format "<u>w</u>ords" (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

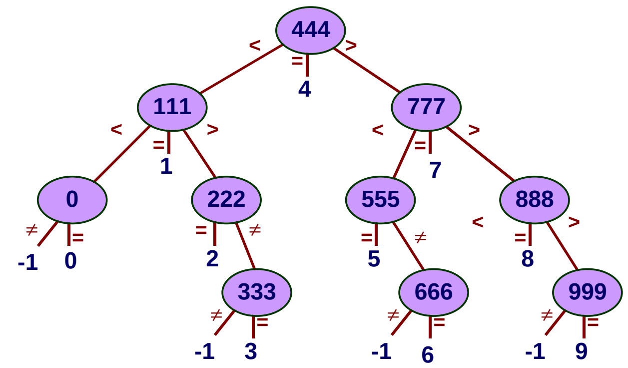
```
    movl 8(%ebp),%eax   # get x
    cmpl $444,%eax      # x:444
    je L8
    jg L16
    cmpl $111,%eax      # x:111
    je L5
    jg L17
    testl %eax,%eax     # x:0
    je L4
    jmp L14

    . . .
```

- 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