Machine-Level Programming II: Control Flow

Today

- Condition codes
- Control flow structures

Next time

- Procedures

Fall 2011

Condition codes

- Single bit registers

`CF`	Carry Flag	`SF`	Sign Flag
`ZF`	Zero Flag	`OF`	Overflow Flag

- Implicitly set by arithmetic operations

  `addl source,destination`

  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

- 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

- 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

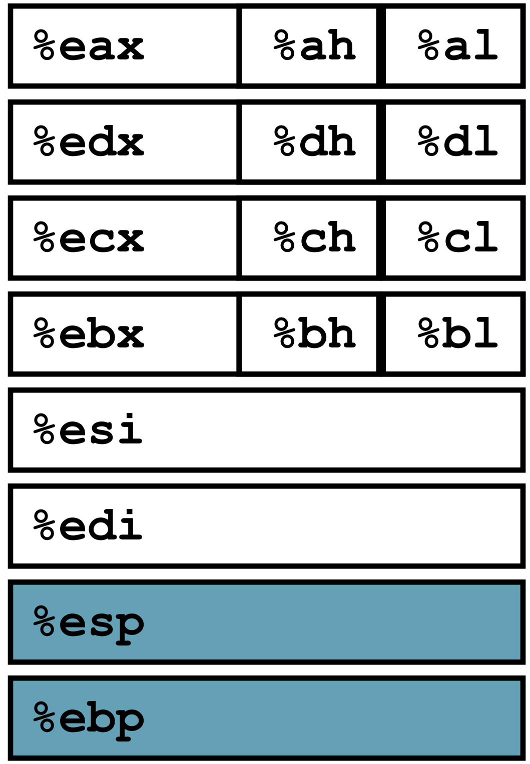
  – `testl b,a` like computing `a&b` without setting destination

  – `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
  - 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!

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)

Checkpoint

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      }
        cmpl %eax,%edx          } Body
        jle L9                  }
        movl %edx,%eax          }
L9:

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

Conditional branch example

```
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 ≤ 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;
}
```

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
```

- Registers

```
%edx   x
%eax   result
```

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:
```


Monday, October 10, 2011

Checkpoint

"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: $x^p = z_0 \cdot z_1^{\,2} \cdot (z_2^{\,2})^{\,2} \cdot \ldots \cdot (\ldots((z_{n-1}^{\,2})^{\,2})\ldots)^{\,2}$

    $z_i = 1$ **when** $p_i = 0$

    $z_i = x$ **when** $p_i = 1$

    ***n–1* times**
  - 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

- 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 (otool on Mac's)

  `objdump code-examples –s --section=.rodata`
  - Show everything in indicated segment.
- Hard to read
  - Jump table entries shown with reversed byte ordering
  - E.g., `30870408` really means `0x08048730`

```
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 = %
 …
```

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

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

```
/* 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;
  }
}
```

Sparse switch code

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

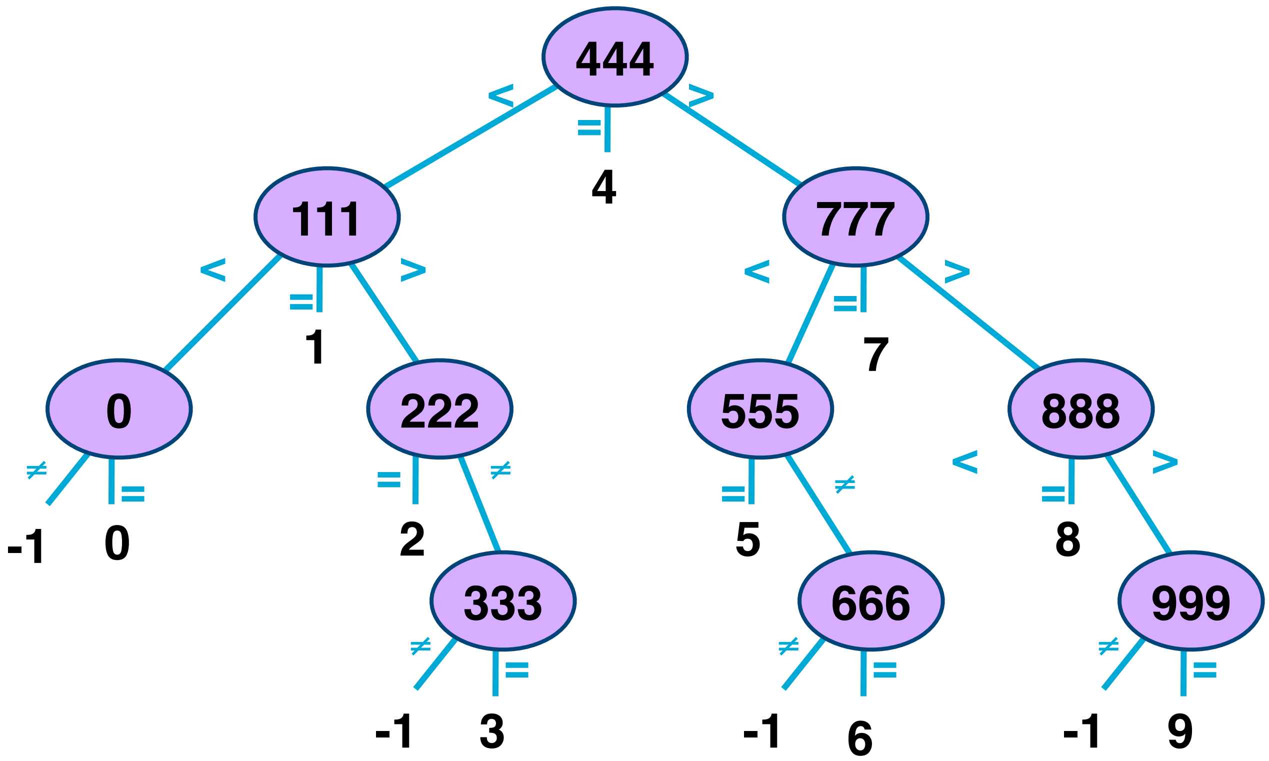
```
    movl 8(%ebp),%eax  # get x
    cmpl $444,%eax     # x:444
    je L8
    jg L16
    cmpl $111,%eax     # x:111
    je L5
    jg L17
    testl %eax,%eax    # x:0
    je L4
    jmp L14

    . . .
```

```
    . . .
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 → do-while form
  – Large switch statements use jump tables
- Conditions in CISC
  – Machines generally have condition code registers
- Conditions in RISC
  – Use general registers
  – Special comparison instructions