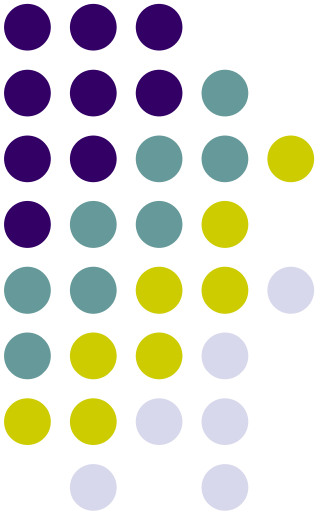
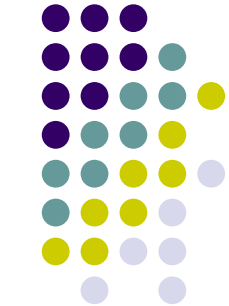
Computer Organization: A Programmer's Perspective

Machine-Level Programming (2: Conditions and Branches)



Gal A. Kaminka
galk@cs.biu.ac.il

Condition Codes



Single Bit Registers

- `CF` Carry Flag (unsigned)
- `SF` Sign Flag (for signed)
- `ZF` Zero Flag
- `OF` Overflow Flag (for signed)

Implicitly Set By Arithmetic Operations

`addl` *Src,Dest* *same as* C analog: `t = a + b`

CF set if carry out from most significant bit
Used to detect unsigned overflow

ZF set if `t == 0`

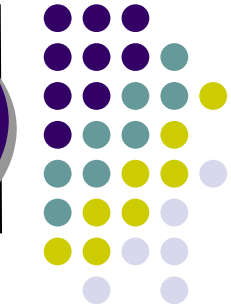
SF set if `t < 0`

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

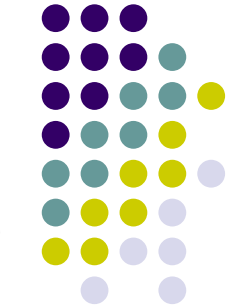
`testl` *Src2,Src1* *like Src1&Src2 in C*

- Sets condition codes based on value of *Src1* `&` *Src2*
- Useful to have one of the operands be a mask

ZF set when `a&b == 0`

SF set when `a&b < 0`

Reading Condition Codes

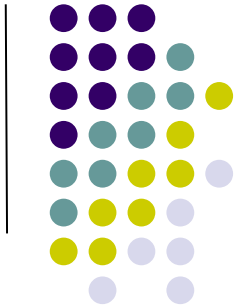


SetX Instructions

- Set lower byte of destination, no change to upper 7 bytes
- 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 (32 bits)

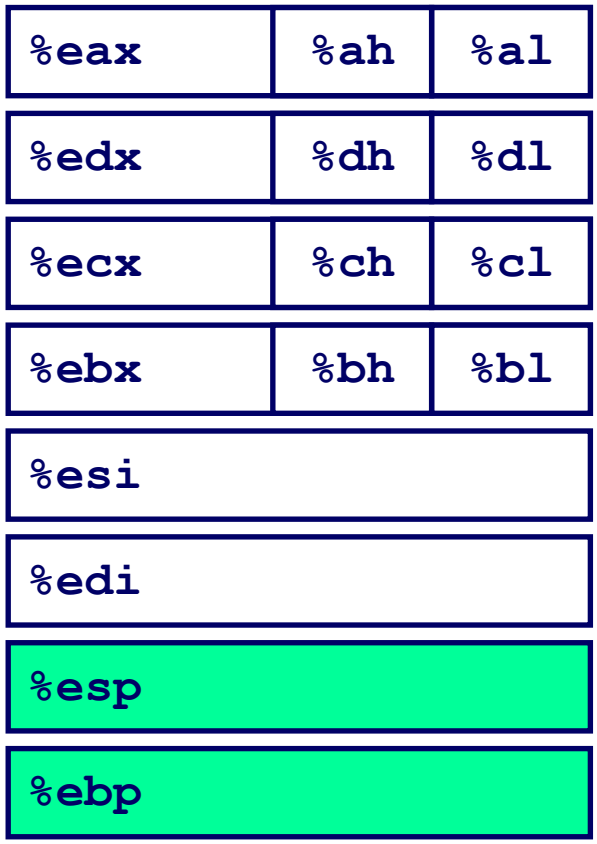
- Set single byte based on combinations of condition codes
- One of 8 addressable byte registers
  - Embedded within first 4 integer registers
  - Does not alter remaining 3 bytes
  - Typically use `movzbl` to finish job

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

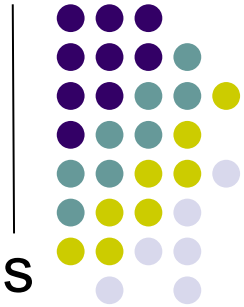
Body

```
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!



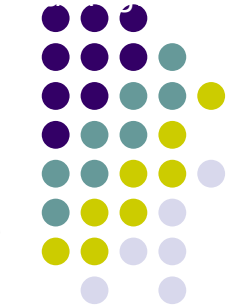
Jumping



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 (Old Style, 64 bits)



- Generation

```
> gcc -Og -S -fno-if-conversion control.c
```

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

```
absdiff:
    cmpq    %rsi, %rdi   # x:y
    jle     .L4
    movq    %rdi, %rax
    subq    %rsi, %rax
    ret
.L4:                     # x <= y
    movq    %rsi, %rax
    subq    %rdi, %rax
    ret
```

Register	Use(s)
%rdi	Argument x
%rsi	Argument y
%rax	Return value

Conditional Move

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

Register	Use(s)
%rdi	Argument **x**
%rsi	Argument **y**
%rax	Return value

```
absdiff:
    movq    %rdi, %rax   # x
    subq    %rsi, %rax   # result = x-y
    movq    %rsi, %rdx
    subq    %rdi, %rdx   # eval = y-x
    cmpq    %rsi, %rdi   # x:y
    cmovle  %rdx, %rax   # if <=, result = eval
    ret
```

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

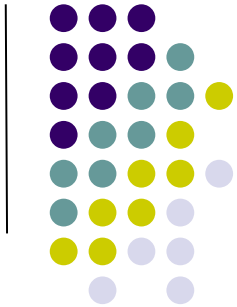
```
val = p ? *p : 0;
```

- Both values get computed
- May have undesirable effects

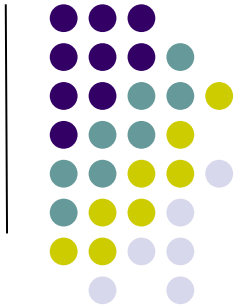
Computations with side effects

```
val = x > 0 ? x*=7 : x+=3;
```

- Both values get computed
- Must be side-effect free



"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;
}
```

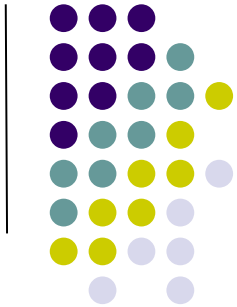
Goto Version

```
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;
}
```

32 bit 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

"While" Loop #1 (bad)

C Code

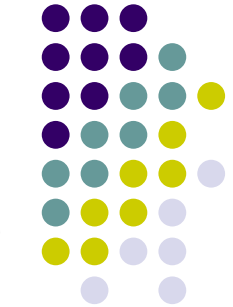
```
int fact_while
  (int x)
{
  int result = 1;
  while (x > 1) {
    result *= x;
    x = x-1;
  };
  return result;
}
```

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;
}
```

Must jump out of loop if test fails: inefficient!

"While" Loop #2 (good)



C Code

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

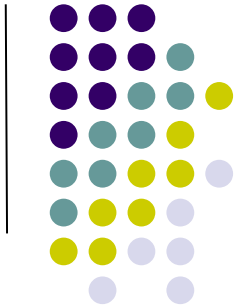
Second Goto Version

```
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;
}
```

Guards loop entry with extra test

Uses same inner loop as do-while version: efficient!

General "While" Translation



C Code

```
while (Test)
  Body
```

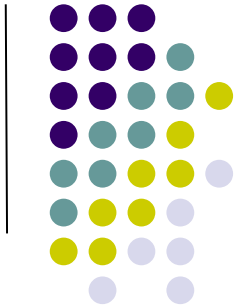
Do-While Version

```
  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



```
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
```

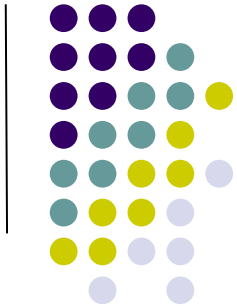
Update

```
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 ;
}
```

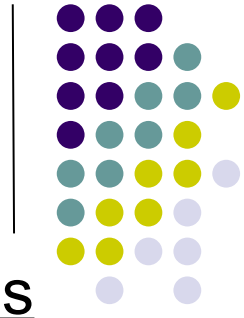
Do-While Version

```
  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:
```

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 only few cases
- Jump Table
  - Lookup branch target
  - Avoids conditionals
  - Possible when cases are small integer consts
- GCC: Picks one method

Bug in example code

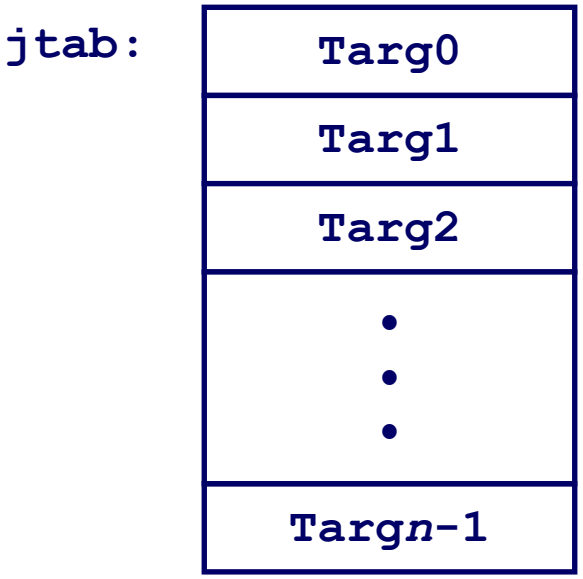
- No default given

Jump Table Structure

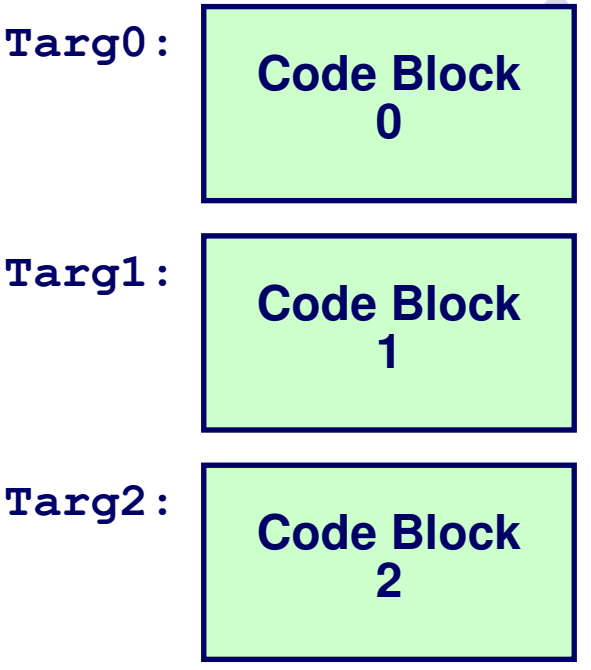
Switch Form

```
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 (not valid C)

```
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) {
    • • •
  }
}
```

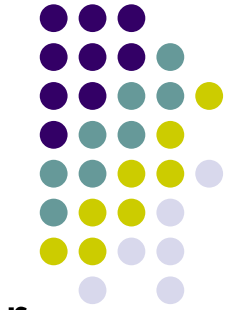
Enumerated Values

```
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

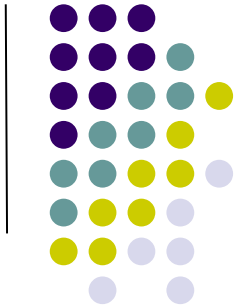
Register `%eax` set to `op` at beginning of procedure

This becomes the returned value

Advantage of Jump Table:

k-way branch in *O*(1)

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)
```

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.

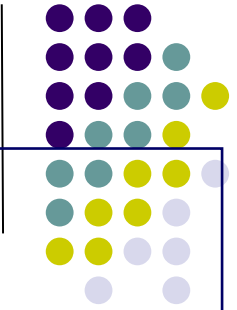
Difficult to read

- 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



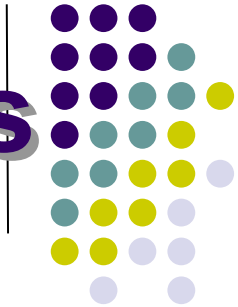
```
8048730:b8 2b 00 00 00   movl   $0x2b,%eax
8048735:eb 25            jmp    804875c <unparse_symbol+0x44>
8048737:b8 2a 00 00 00   movl   $0x2a,%eax
804873c:eb 1e            jmp    804875c <unparse_symbol+0x44>
804873e:89 f6            movl   %esi,%esi
8048740:b8 2d 00 00 00   movl   $0x2d,%eax
8048745:eb 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

Done automatically by compiler, (remember the -O flag?)

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
```

שאלות?