# The Hardware/Software Interface

CSE351 Winter 2013

## x86 Programming II

# Today's Topics: control flow

- Condition codes
- Conditional and unconditional branches
- Loops

# Conditionals and Control Flow

- **A conditional branch is sufficient to implement most control flow constructs offered in higher level languages**
  - if (condition) then {...} else {…}
  - while (condition) {…}
  - do {…} while (condition)
  - for (initialization; condition; iterative) {...}
- **Unconditional branches implement some related control flow constructs**
  - break, continue
- **In x86, we'll refer to branches as "jumps" (either conditional or unconditional)**

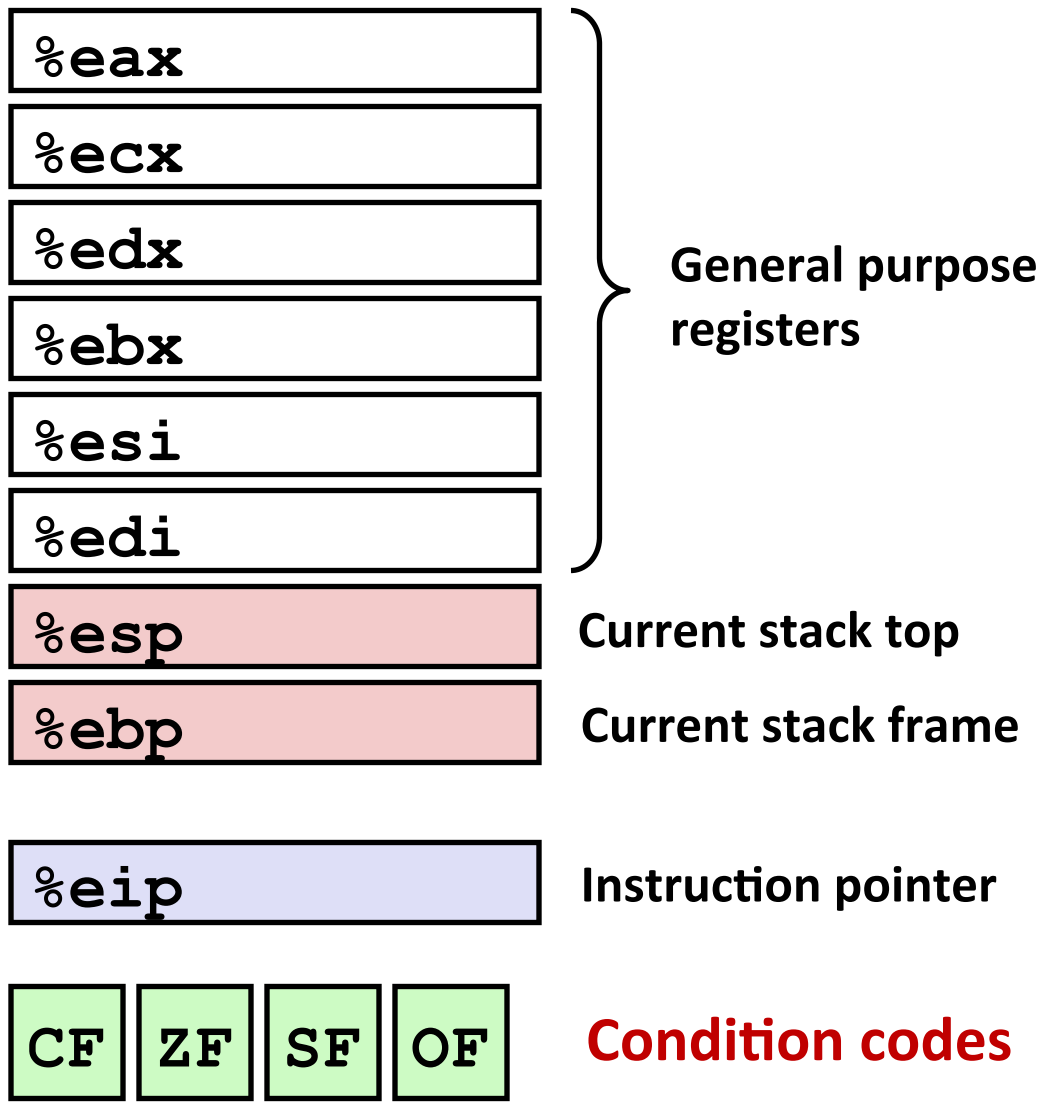
# Jumping

- **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) |

# Processor State (IA32, Partial)

- **Information about currently executing program**
  - Temporary data ( **%eax**, …)
  - Location of runtime stack ( **%ebp**,**%esp**)
  - Location of current code control point ( **%eip** )
  - Status of recent tests ( **CF**,**ZF**,**SF**,**OF** )



# Condition Codes (Implicit Setting)

- **Single-bit registers**

  **`CF`** Carry Flag (for unsigned)  **`SF`** Sign Flag (for signed)

  **`ZF`** Zero Flag  **`OF`** Overflow Flag (for signed)

- **Implicitly set (think of it as side effect) by arithmetic operations**

  Example: **`addl/addq`** *Src,Dest* ↔ **`t = a+b`**

  - **CF set** if carry out from most significant bit (unsigned overflow)
  - **ZF set** if `t == 0`
  - **SF set** if `t < 0` (as signed)
  - **OF set** if two's complement (signed) overflow
    `(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`

- ***Not* set by `lea` instruction (beware!)**

- **Full documentation (IA32): http://www.jegerlehner.ch/intel/IntelCodeTable.pdf**

# Condition Codes (Explicit Setting: Compare)

- **Single-bit registers**

  **`CF`** Carry Flag (for unsigned) **`SF`** Sign Flag (for signed)

  **`ZF`** Zero Flag **`OF`** Overflow Flag (for signed)

- **Explicit Setting by Compare Instruction**

  **`cmpl/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`** (as signed)
  - **OF set** if two's complement (signed) overflow

    **`(a>0 && b<0 && (a-b)<0) || (a<0 && b>0 && (a-b)>0)`**

# Condition Codes (Explicit Setting: Test)

- **Single-bit registers**

  **`CF`** Carry Flag (for unsigned) **`SF`** Sign Flag (for signed)

  **`ZF`** Zero Flag **`OF`** Overflow Flag (for signed)

- **Explicit Setting by Test instruction**

  **`testl`**/**`testq`** *Src2,Src1*

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

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

  - **ZF set** if **`a&b == 0`**
  - **SF set** if **`a&b < 0`**

  - **`testl %eax, %eax`**
    - Sets SF and ZF, check if eax is +,0,-

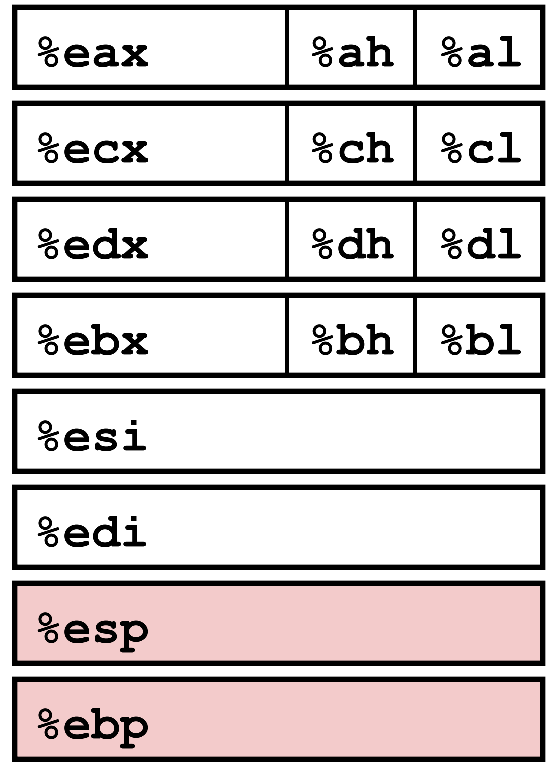
# Reading Condition Codes

- **SetX Instructions**
  - Set a single byte to 0 or 1 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 to 0 or 1 based on combination of condition codes
- **One of 8 addressable byte registers**
  - Does not alter remaining 3 bytes
  - Typically use **`movzbl`** to finish job




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

**Body:** **y at 12(%ebp), x at 8(%ebp)**

```
movl 12(%ebp),%eax
cmpl %eax,8(%ebp)
setg %al
movzbl %al,%eax
```

**What does each of these instructions do?**

# Reading Condition Codes (Cont.)

- **SetX Instructions:**
  Set single byte to 0 or 1 based on combination of condition codes
- **One of 8 addressable byte registers**
  - Does not alter remaining 3 bytes
  - Typically use **`movzbl`** to finish job

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

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

**Body:** y at 12(%ebp), x at 8(%ebp)

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

(x – y) → Compare x and 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` | `~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 absdiff(int x, int y)
{
    int result;
    if (x > y) {
        result = x-y;
    } else {
        result = y-x;
    }
    return result;
}
```

```
absdiff:
    pushl   %ebp                 } Setup
    movl    %esp, %ebp
    movl    8(%ebp), %edx        } Body1
    movl    12(%ebp), %eax
    cmpl    %eax, %edx
    jle     .L7
    subl    %eax, %edx
    movl    %edx, %eax
.L8:
    leave                        } Finish
    ret
.L7:
    subl    %edx, %eax           } Body2
    jmp     .L8
```

# Conditional Branch Example (Cont.)

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

```
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

# 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;
}
```

```
int x       %edx
int y       %eax
```

```
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
```

# 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;
}
```

```
int x        %edx
int y        %eax
```

```
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
```

# 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;
}
```

| | |
|---|---|
| int x | %edx |
| int y | %eax |

```
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
```

# 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;
}
```

| | |
|---|---|
| int x | %edx |
| int y | %eax |

```
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
```

# 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;
}
```

| | |
|---|---|
| int x | %edx |
| int y | %eax |

```
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
```

# General Conditional Expression Translation

## C Code

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

```
val = x>y ? x-y : y-x;
```

```
if (Test)
  val = Then-Expr;
else
  val = Else-Expr;
```

## 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

- How might you make this more efficient?

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

- **Conditional move instruction**
  - `cmovC` src, dest
  - Move value from src to dest if condition *C* holds
  - More efficient than conditional branching (simple control flow)
  - But overhead: both branches are evaluated

# PC Relative Addressing

```
0x100      cmp   r2, r3      0x1000
0x102      je    0x70        0x1002
0x104      …                 0x1004
…          …                 …
0x172      add   r3, r4      0x1072
```

- PC relative branches are relocatable
- Absolute branches are not

# Compiling Loops

**C/Java code:**

```
while ( sum != 0 ) {
   <loop body>
}
```

**Machine code:**

```
loopTop:    cmpl  $0, %eax
            je    loopDone
              <loop body code>
            jmp   loopTop
loopDone:
```

- **How to compile other loops should be straightforward**
  - The only slightly tricky part is to be sure where the conditional branch occurs: top or bottom of the loop
- **How would for(i=0; i<100; i++) be implemented?**

# "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
  movl %esp,%ebp
  movl $1,%eax
  movl 8(%ebp),%edx

.L11:
  imull %edx,%eax
  decl %edx
  cmpl $1,%edx
  jg .L11

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

**Translation?**

# "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:*** {
  
  $Statement_1$;
  
  $Statement_2$;
  
  …
  
  $Statement_n$;
  
  }

- ***Test*** **returns integer**
  
  = 0 interpreted as false
  
  ≠ 0 interpreted as true

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

- Used by GCC for both IA32 & x86-64
- First iteration jumps over body computation within loop straight to test

# "While" Loop Example

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

```
# 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: Square-and-Multiply

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

- **Algorithm**
  - Exploit bit representation: $p = p_0 + 2p_1 + 2^2 p_2 + \ldots 2^{n-1} p_{n-1}$
  - 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 int p)
{
   int result;
   for (result = 1; p != 0; p = p>>1) {
      if (p & 0x1)
         result *= x;
      x = x*x;
   }
   return result;
}
```

| before iteration | result | x=3 | p=10 |
|---:|---:|---:|---:|
| 1 | 1 | 3 | $10=1010_2$ |
| 2 | 1 | 9 | $5=101_2$ |
| 3 | 9 | 81 | $2=10_2$ |
| 4 | 9 | 6561 | $1=1_2$ |
| 5 | 59049 | 43046721 | $0_2$ |

# "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;
}
```

**Goto Version**

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

# For-Loop: Compilation

**For Version**

```
for (Init; Test; Update )

    Body
```

**Goto Version**

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

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

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

# Quick Review

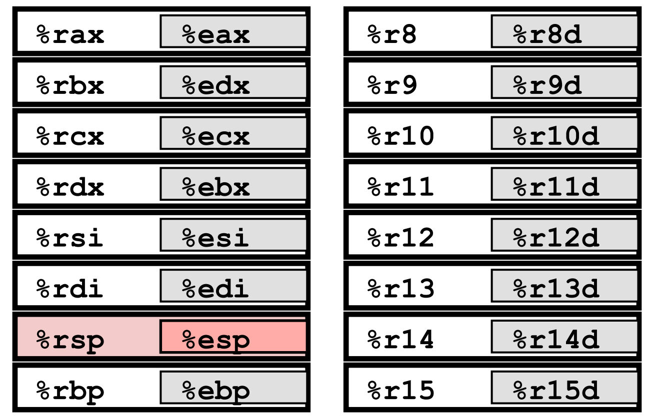
- Complete memory addressing mode
  - `(%eax), 17(%eax), 2(%ebx, %ecx, 8), …`

- Arithmetic operations that do set condition codes
  - `subl %eax, %ecx          # ecx = ecx + eax`
  - `sall $4,%edx             # edx = edx << 4`
  - `addl 16(%ebp),%ecx       # ecx = ecx + Mem[16+ebp]`
  - `imull %ecx,%eax          # eax = eax * ecx`

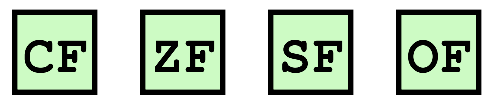
- Arithmetic operations that do NOT set condition codes
  - `leal 4(%edx,%eax),%eax   # eax = 4 + edx + eax`

# Quick Review

- **x86-64 vs. IA32**
  - Integer registers: **16 x 64-bit** vs. **8 x 32-bit**
  - **`movq, addq`**, … vs. **`movl, addl`**, …
    - movq -> "move quad word" or 4*16-bits
  - x86-64: better support for passing function arguments in registers




- **Control**
  - Condition code registers
  - Set as side effect or by **`cmp, test`**
  - Used:
    - Read out by setx instructions (**`setg, setle`**, …)
    - Or by conditional jumps (**`jle .L4, je .L10, …`**)
    - Or by conditional moves (**`cmovle %edx, %eax`**)



# Quick Review

- **Do-While loop**

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

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

- **While-Do loop**

While version
```
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:
```

*or*

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

# 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**
  - Loops converted to do-while form
  - Large switch statements use jump tables
  - Sparse switch statements may use decision trees (see text)
- **Conditions in CISC**
  - CISC machines generally have condition code registers