Imperial College London

# 113: Architecture

Spring 2018

*Lecture:* Machine-Level Programming II

**Instructor:** Dr. Jana Giceva

# Update on materials

- Library update – course book

  "Computer Systems: A Programmer's Perspective"

  - More tokens are provided for the e-version of the 2nd edition
  - More hard copies were ordered for the 3rd edition
  - If you want a copy of the 3rd edition and it is not available, please place a hold request https://www.imperial.ac.uk/admin-services/library/use-the-library/requesting-a-book/
  - or write an email to Ann Brew (ann.brew@imperial.ac.uk)

- Online compiler – https://godbolt.org/

# Today: Arithmetic and condition codes

- **Arithmetic and Logic Operations**
- Control Flow: Condition Codes
- Conditional control and data movement

# Address computation instruction

- `lea` **src, dest**
  - "lea" stands for ***load effective address***
  - **src** is memory address mode expression
  - set **dest** to address denoted by expression
  - **dest** is a register
- **Used when:**
  - computing addresses **without** a memory reference
  - computing arithmetic expressions of the form $\boldsymbol{x} + \boldsymbol{k} * \boldsymbol{y}$, where *k* = 1, 2, 4 or 8

*Code example:*

```
long mult_12(long x) {
    return x*12;
}
```

*Generated assembly with optimization:*

```
mult_12:
leaq (%rdi,%rdi,2), %rax
salq $2, %rax
ret
```

| Register | Use |
|---|---|
| `%rdi` | Argument `x` |
| `%rax` | Return value |

# Example: `lea` vs `mov`

**Registers**

| | |
|---|---|
| %rax | |
| %rbx | |
| %rcx | 0x4 |
| %rdx | 0x100 |
| %rdi | |
| %rsi | |

**Memory**

| | |
|---|---|
| 0x400 | 0x120 |
| 0xF | 0x118 |
| 0x8 | 0x110 |
| 0x10 | 0x108 |
| 0x1 | 0x100 |

```
leaq (%rdx,%rcx,4), %rax
movq (%rdx,%rcx,4), %rbx
leaq (%rdx), %rdi
movq (%rdx), %rsi
```

# Example: `lea` vs `mov`

**Registers**

| | |
|---|---|
| %rax | 0x110 |
| %rbx | 0x8 |
| %rcx | 0x4 |
| %rdx | 0x100 |
| %rdi | 0x100 |
| %rsi | 0x1 |

**Memory**

| | |
|---|---|
| 0x400 | 0x120 |
| 0xF | 0x118 |
| 0x8 | 0x110 |
| 0x10 | 0x108 |
| 0x1 | 0x100 |

```
leaq (%rdx,%rcx,4), %rax
movq (%rdx,%rcx,4), %rbx
leaq (%rdx), %rdi
movq (%rdx), %rsi
```

# Example x86 Arithmetic Operations

- Two-operand instructions (longword variants)
- Watch out for argument order!

| Instruction | Operation | Notes |
|---|---|---|
| **addl** *src,dest* | dest = dest + src | Addition |
| **subl** *src,dest* | dest = dest - src | Subtraction |
| **imull** *src,dest* | dest = dest * src | Multiplication |
| **sall** *src,dest* | dest = dest << src | Shift arithmetic left |
| **sarl** *src,dest* | dest = dest >> src | Shift arithmetic right |
| **xorl** *src,dest* | dest = dest ^ src | Bitwise xor |
| **andl** *src,dest* | dest = dest & src | Bitwise and |
| **orl** *src,dest* | dest = dest \| src | Bitwise or |

Quick way to multiply and divide by powers of 2

# Example x86 Arithmetic Operations

- One-operand instructions (longword variants)

| Instruction | Operation | Notes |
|---|---|---|
| **`incl`** *dest* | dest = dest + 1 | Increment by 1 |
| **`decl`** *dest* | dest = dest - 1 | Decrement by 1 |
| **`negl`** *dest* | dest = -dest | Negate |
| **`notl`** *dest* | dest = ~dest | Bitwise not |

- See the book for more instructions

# Arithmetic expression example

| Register | Use(s) |
|---|---|
| %rdi | x |
| %rsi | y |
| %rdx | z, t4 |
| %rax | t1, t2, rval |
| %rcx | t5 |

*Code example:*

```
int arithmetic
(int x, int y, int z) {
    int t1 = x + y;
    int t2 = z + t1;
    int t3 = x + 4;
    int t4 = y * 48;
    int t5 = t3 + t4;
    int ret = t2 * t5;
    return ret;
}
```

*Generated assembly with optimization:*

```
arithmetic:

  leal   (%rdi,%rsi),%eax    # eax = x+y
  addl   %edx, %eax          # edx = z+eax
  leal   (%rsi,%rsi,2),%edx  # edx = y*3
  sall   $4, %edx            # edx = edx*16
  leal   4(%rdi,%rdx),%ecx   # ecx = x+4+edx
  imull  %ecx, %eax          # eax = eax*ecx
  ret
```

# Boolean expression example

| Register | Use |
|---|---|
| %edi | x, t1, t2 |
| %esi | y |
| %eax | t3, ret |

*Code example:*

```
int logical
(int x, int y) {
    int t1 = x ^ y;
    int t2 = t1 >> 17;
    int t3 = (1<<13) - 7;
    int ret = t2 & t3;
    return ret;
}
```

*Generated assembly with optimization:*

```
logical:

  xorl %esi, %edi       # edi = x ^ y
  sarl $17, %edi        # edi = edi >> 17
  movl %edi, %eax       #
  andl $8185, %eax      # eax = t2 & 8185
  ret
```

- Generating the mask `t3`

$$2^{13} = 8192, 2^{13} - 7 = 8185$$

# Today: Arithmetic and condition codes

- Arithmetic and Logic Operations
- **Control Flow: Condition Codes**
- Conditional control  and data movement

# Control Flow

*Code example:*

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

*Assembly*

```
max:
  ???
  movq  %rdi, %rax
  ???
  ???
  movq  %rsi, %rax
  ???
  ret
```

| Register | Use |
|---|---|
| %rdi | Argument x |
| %rsi | Argument y |
| %rax | Return value |

# Control Flow

*Code example:*

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

*Assembly*

```
max:
   if x<=y then jump to else
   movq  %rdi, %rax
   jump to done
else:
   movq  %rsi, %rax
done:
   ret
```

Conditional jump

Unconditional jump

| Register | Use |
|---|---|
| %rdi | Argument x |
| %rsi | Argument y |
| %rax | Return value |

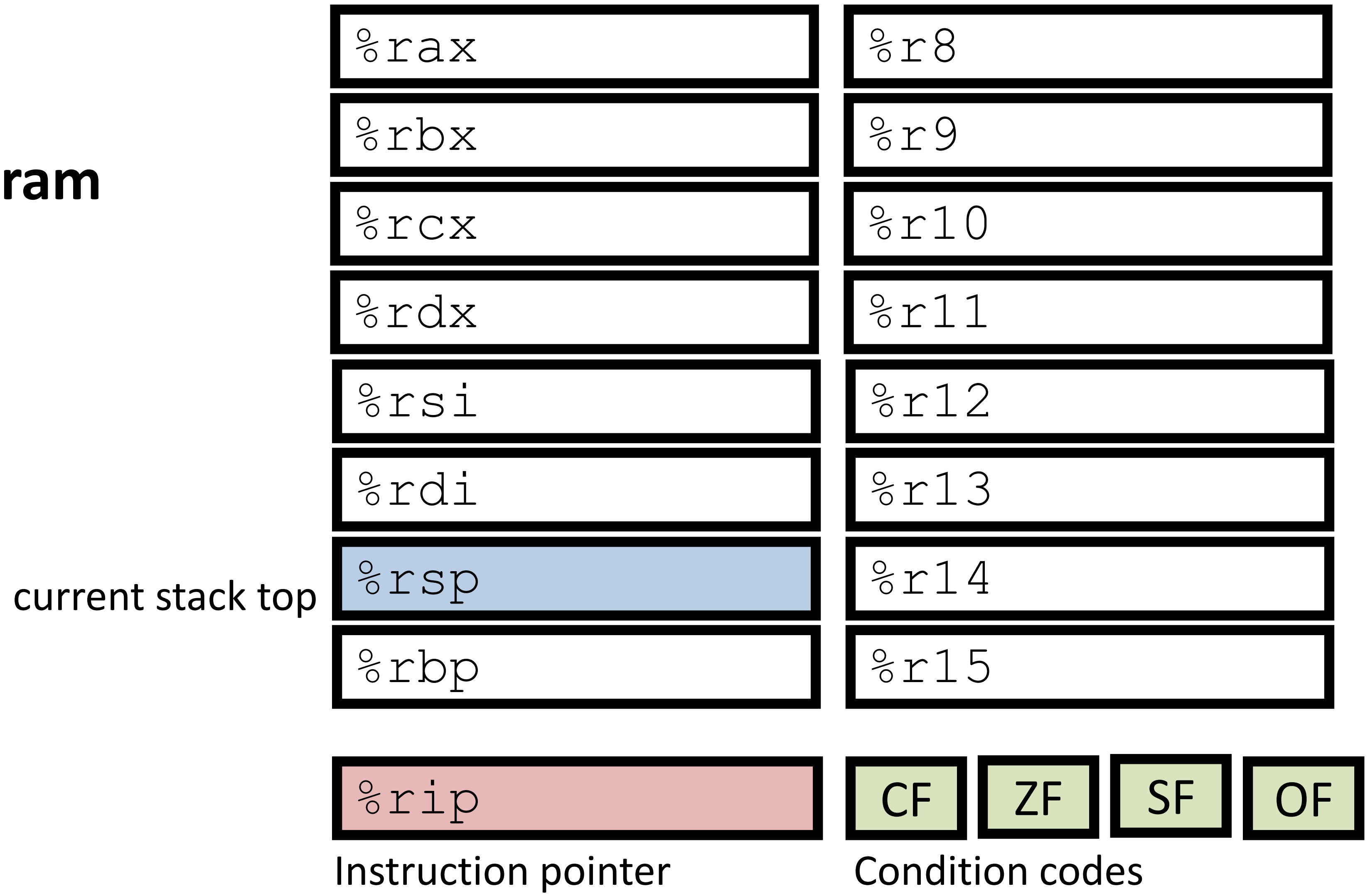
# Conditionals and Control Flow

- **Conditional branch/jump**
  - Jump to somewhere else if some *condition* is true
    otherwise execute the next instruction
- **Unconditional branch/jump**
  - *Always* jump when you get to this instruction
  - For example: `break`, `continue`

- They can implement most control flow constructs in high-level languages:
  - **`if`** (*condition*) **`then`** {…} **`else`** {…}
  - **`while`** (*condition*) {…}
  - **`do`** {…} **`while`** (*condition*)
  - **`for`** (*initialization*; *condition*; *iterative*) {…}
  - **`switch`** {…}

# Processor State (x86-64, partial)

- **Information about currently executing program**
  - Temporary data (`%rax`, …)
  - Location of runtime stack (**`%rsp`**)
  - Location of current code control point (**`%rip`**, …)
  - Status of recent tests (**CF**, **ZF**, **SF**, **OF**)



# Condition codes (implicit setting)

- **Single bit registers**

  **CF** – Carry Flag (for unsigned)
  **ZF** – Zero Flag
  **SF** – Sign Flag (for signed)
  **OF** – Overflow Flag (for signed)

- **Implicitly set** (think of it as a side effect) **by arithmetic operations** (not by `lea`)

  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)`

# Condition codes (<u>explicit</u> setting: compare)

- **Explicit setting by a `compare` instruction**
  `cmpl/cmpq` *Src2,Src1*

  Example: `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 (<u>explicit</u> setting: test)

- **Explicit setting by a `test` instruction**

  `testl/testq` *Src2,Src1*

  Example: `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*** when `a&b == 0`
  - ***SF set*** when `a&b < 0`
- `testl %eax, %eax`
  - Sets SF and ZF, check if eax is +,0,-

# Reading Condition codes

- `set*` ***instructions***: set low order byte to 0 or 1 based on computation of condition codes. Does not alter the remaining bytes.

| SetX instruction | Condition | Description |
|---|---|---|
| **`sete`** *dst* | ZF | Equal / Zero |
| **`setne`** *dst* | ~ZF | Not equal / Not zero |
| **`sets`** *dst* | SF | Negative |
| **`setns`** *dst* | ~SF | Nonnegative |
| **`setg`** *dst* | ~(SF^OF)&~ZF | Greater (Signed) |
| **`setge`** *dst* | ~(SF^OF) | Greater or equal (Signed) |
| **`setl`** *dst* | (SF^OF) | Less (Signed) |
| **`setle`** *dst* | (SF^OF)\|ZF | Less or equal (Signed) |
| **`seta`** *dst* | ~CF&ZF | Above (unsigned) |
| **`setb`** *dst* | CF | Below (unsigned) |

# Reading condition codes (cont.)

- `set*` **instructions:**
  set single byte based on combination of condition codes

- **One of 16 addressable byte registers**
  - Does not alter remaining 3-7 bytes
  - Typically use `movzbl` to finish job

| %rax | %eax | %ah | %al |
|---|---|---|---|

| Register | Use |
|---|---|
| %edi | x |
| %esi | y |

*Code example:*

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

*Body*

```
cmpl %esi, %edi     # compare x : y
setg %al            # al = x > y
movzbl %al, %eax    # zero rest of %rax
```

# Of interest: `movz` and `movs`

`movz__` *src, regDest* *Move with zero extension*

`movs__` *src, regDest* *Move with sign extension*

- Copy from a *smaller* source value to a *larger* destination
- Source can be memory or register; Destination *must* be a register
- Fill remaining bits of dest with **zero**(`mov`**`z`**) or **sign bit** (`mov`**`s`**)

**`movz`*SD*** / **`movs`*SD***

***S*** – size of source (**`b`**=1 byte, **`w`**=2)

***D*** – size of dest (**`w`**=2 bytes, **`l`**=4, **`q`**=8)

*Example:* `movzbq %al, %rbx`

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| `%rax` | `0x??` | `0x??` | `0x??` | `0x??` | `0x??` | `0x??` | `0x??` | `0xFF` |
| `%rbx` | `0x00` | `0x00` | `0x00` | `0x00` | `0x00` | `0x00` | `0x00` | `0xFF` |

zero filled

# Of interest: `movz` and `movs`

`movz__` *src, regDest* *Move with zero extension*

`movs__` *src, regDest* *Move with sign extension*

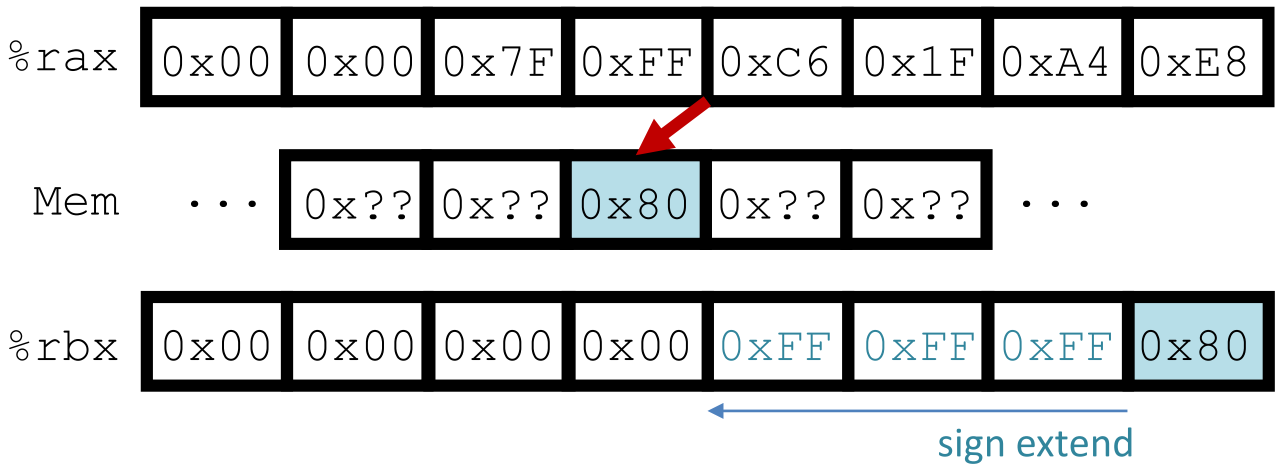
- Copy from a *smaller* source value to a *larger* destination
- Source can be memory or register; Destination *must* be a register
- Fill remaining bits of dest with **zero**(`movz`) or **sign bit** (`movs`)

**`movz`*SD*** / **`movs`*SD***

***S*** – size of source (**`b`**=1 byte, **`w`**=2)

***D*** – size of dest (**`w`**=2 bytes, **`l`**=4, **`q`**=8)

*Example:* `movsbl (%rax), %ebx`



# Jumping

- `j*` ***Instructions***: Jump to different part of code indicated by ***target*** argument
  Conditional jump depends on ***condition code registers***

| Instruction | Condition | Description |
|---|---|---|
| **`jmp`** *target* | `1` | Unconditional |
| **`je`** *target* | `ZF` | Equal / Zero |
| **`jne`** *target* | `~ZF` | Not Equal / Not Zero |
| **`js`** *target* | `SF` | Negative |
| **`jns`** *target* | `~SF` | Nonnegative |
| **`jg`** *target* | `~(SF^OF)&~ZF` | Greater (signed) |
| **`jge`** *target* | `~(SF^OF)` | Greater or equal (signed) |
| **`jl`** *target* | `(SF^OF)` | Less (signed) |
| **`jle`** *target* | `(SF^OF)\|ZF` | Less or equal (signed) |
| **`ja`** *target* | `~CF&~ZF` | Above (unsigned) |
| **`jb`** *target* | `CF` | Below (unsigned) |

# Choosing instructions for conditionals

| `compare` or `test` | | `cmp b,a` | `test a,b` |
|---|---|---|---|
| `je` | "Equal" | `a == b` | `a&b == 0` |
| `jne` | "Not equal" | `a != b` | `a&b != 0` |
| `js` | "Sign" (negative) | | `a&b < 0` |
| `jns` | (non-negative) | | `a&b >= 0` |
| `jg` | "Greater" | `a > b` | `a&b > 0` |
| `jge` | "Greater or equal" | `a >= b` | `a&b >= 0` |
| `jl` | "Less" | `a < b` | `a&b < 0` |
| `jle` | "Less or equal" | `a <= b` | `a&b <= 0` |
| `ja` | "Above" (unsigned >) | `a > b` | |
| `jb` | "Below" (unsigned <) | `a < b` | |

`jump` or `set`

*Examples:*

```
        cmp 5, (%rax)
je:   (%rax) == 5
jne:  (%rax) != 5
jg:   (%rax) >  5
jl:   (%rax) <  5
```

```
        test %rdi, %rdi
je:     %rdi == 0
jne:    %rdi != 0
jg:     %rdi >  0
jl:     %rdi <  0
```

```
        test %rax, 0x1
je:     %rax_LSB == 0
jne:    %rax_LSB == 1
```

# Today: Arithmetic and condition codes

- Arithmetic and Logic Operations
- Control: Condition Codes
- **Conditional control and data movement**

# Conditional branch example

- Generation

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

| Register | Use |
|---|---|
| `%rdi` | Argument `x` |
| `%rsi` | Argument `y` |
| `%rax` | Return value |

*Code example:*

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

*Assembly*

```
abs_diff:
    ???
    ???
    movq    %rdi, %rax
    subq    %rsi, %rax
    jmp     .L5
.L4:                         # x <= y
    movq    %rsi, %rax
    subq    %rdi, %rax
.L5:
    ret
```

# Conditional branch example

- Generation

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

| Register | Use |
|---|---|
| `%rdi` | Argument `x` |
| `%rsi` | Argument `y` |
| `%rax` | Return value |

*Code example:*

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

*Assembly*

```
abs_diff:
    cmpq    %rsi, %rdi    # x:y
    jle     .L4
    movq    %rdi, %rax
    subq    %rsi, %rax
    jmp     .L5
.L4:                      # x <= y
    movq    %rsi, %rax
    subq    %rdi, %rax
.L5:
    ret
```

# General conditional expression translation with jump (`goto`)

- val = *Test* ? *Then_Expr* : *Else_Expr*;

*C/Java code example*

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

C allows `goto` as means of transferring control (`jump`):

- Closer to assembly programming style
- Generally considered **bad** coding style

*Code example with* `goto`*:*

```
    ntest = !Test;
    if (ntest) goto else;
    val = Then_Expr;
    goto done;
else:
    val = Else_Expr;
done:
    ...
```

- Create separate code regions for **then** and **else** expressions
- Execute appropriate one
- Can it be made more efficient?

# Using conditional moves (in x86-64)

- **Conditional move instructions (`cmov*`)**
  - Instruction supports:

    `if (Test) Dest ← Src`
  - Move value from **`src`** to **`dest`** if condition **`Test`** holds

- **Why do we use it?**
  - More efficient than conditional branching (simple control flow)
  - But, there is overhead, as both branches are evaluated.

# Conditional move example

- **Conditional move instructions**
  do the move in case a condition has been satisfied.

| Register | Use |
| --- | --- |
| %rdi | Argument x |
| %rsi | Argument y |
| %rax | Return value |

*Code example:*

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

*Assembly*

```
absdiff:
   movq    %rdi, %rdx   # x
   subq    %rsi, %rdx   # res = x-y
   movq    %rsi, %rax
   subq    %rdi, %rax   # eval = y-x
   cmpq    %rsi, %rdi   # x:y
   ???
   ret
```

# Conditional move example

- **Conditional move instructions**
  do the move in case a condition has been satisfied.

| Register | Use |
|---|---|
| `%rdi` | Argument `x` |
| `%rsi` | Argument y |
| `%rax` | Return value |

*Code example:*

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

*Assembly*

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

# Bad cases for conditional move

- Expensive computations
  - both values get computed
  - makes sense when computations are simple
- Risky computations
  - both values get computed
  - may have undesirable effects
- Computations with side-effects
  - both values get computed
  - must be side-effect free

*Example 1*

```
val = Test(x)
    ? Hard1(x)
    : Hard2(x);
```

*Example 2*

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

*Example 3*

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

# Summary

- `lea` **is address calculation instruction**
  - Does NOT actually go to memory
  - Used to compute address or some arithmetic expression
- **Control flow in x86 is determined by status of Condition Codes**
  - Showed **C**arry, **Z**ero, **S**ign, and **O**verflow, though others exist as well
  - Set flags with arithmetic operations (implicit) or `compare` and `test` (explicit)
  - `set*` instructions read out flag values
  - `j*` instructions use flag values to determine next instruction to execute
  - `cmov*` instructions use flag values to execute a move instruction