x86-64 Programming II

CSE 351 Spring 2021

Instructor:
Ruth Anderson

Teaching Assistants:
Allen Aby
Joy Dang
Alena Dickmann
Catherine Guevara
Corinne Herzog
Ian Hsiao
Diya Joy
Jim Limprasert
Armin Magness
Aman Mohammed
Monty Nitschke
Allie Pfleger
Neil Ryan
Alex Saveau
Sanjana Sridhar
Amy Xu

http://xkcd.com/99/

Administrivia

- hw7 due TONIGHT (4/16) @ 11:59 pm
- Lab 1b, due Monday 4/19
  - Submit `aisle_manager.c`, `store_client.c`, and `lab1Breflect.txt`
- Lab 2 (x86-64) coming soon
  - Learn to read x86-64 assembly and use GDB

- **Questions Docs**: Use @uw google account to access!!
  - https://tinyurl.com/CSE351-21sp-Questions

Extra Credit

- All labs starting with Lab 2 have extra credit portions
  - These are meant to be fun extensions to the labs

- Extra credit points *don't* affect your lab grades
  - From the course policies: "they will be accumulated over the course and will be used to bump up borderline grades at the end of the quarter."
  - Make sure you finish the rest of the lab before attempting any extra credit

Complete Memory Addressing Modes

- **General:**
  - `D(Rb,Ri,S)` Mem[Reg[`Rb`]+Reg[`Ri`]*`S`+`D`]
    - `Rb`: Base register (any register)
    - `Ri`: Index register (any register except `%rsp`)
    - `S`: Scale factor (1, 2, 4, 8) – *why these numbers?*
    - `D`: Constant displacement value (a.k.a. immediate)

- **Special cases** (see CSPP Figure 3.3 on p.181)
  - `D(Rb,Ri)` Mem[Reg[`Rb`]+Reg[`Ri`]+`D`] `(S=1)`
  - `(Rb,Ri,S)` Mem[Reg[`Rb`]+Reg[`Ri`]*`S`] `(D=0)`
  - `(Rb,Ri)` Mem[Reg[`Rb`]+Reg[`Ri`]] `(S=1,D=0)`
  - `(,Ri,S)` Mem[Reg[`Ri`]*`S`] `(Rb=0,D=0)`

Address Computation Examples

%rdx	0xf000
%rcx	0x0100

D(Rb,Ri,S) → Mem[Reg[Rb]+Reg[Ri]*S+D]

Expression	Address Computation	Address
0x8(%rdx)		
(%rdx,%rcx)		
(%rdx,%rcx,4)		
0x80(,%rdx,2)		

Reading Review

- Terminology:
  - Address Computation Instruction (`lea`)
  - Condition codes: Carry Flag (CF), Zero Flag (ZF), Sign Flag (SF), and Overflow Flag (OF)
  - Test (`test`) and compare (`cmp`) assembly instructions
  - Jump (`j*`) and set (`set*`) families of assembly instructions

Review Questions

- Which of the following x86-64 instructions correctly calculates %rax=9*%rdi?

  A. `leaq (,%rdi,9), %rax`

  B. `movq (,%rdi,9), %rax`

  C. `leaq (%rdi,%rdi,8), %rax`

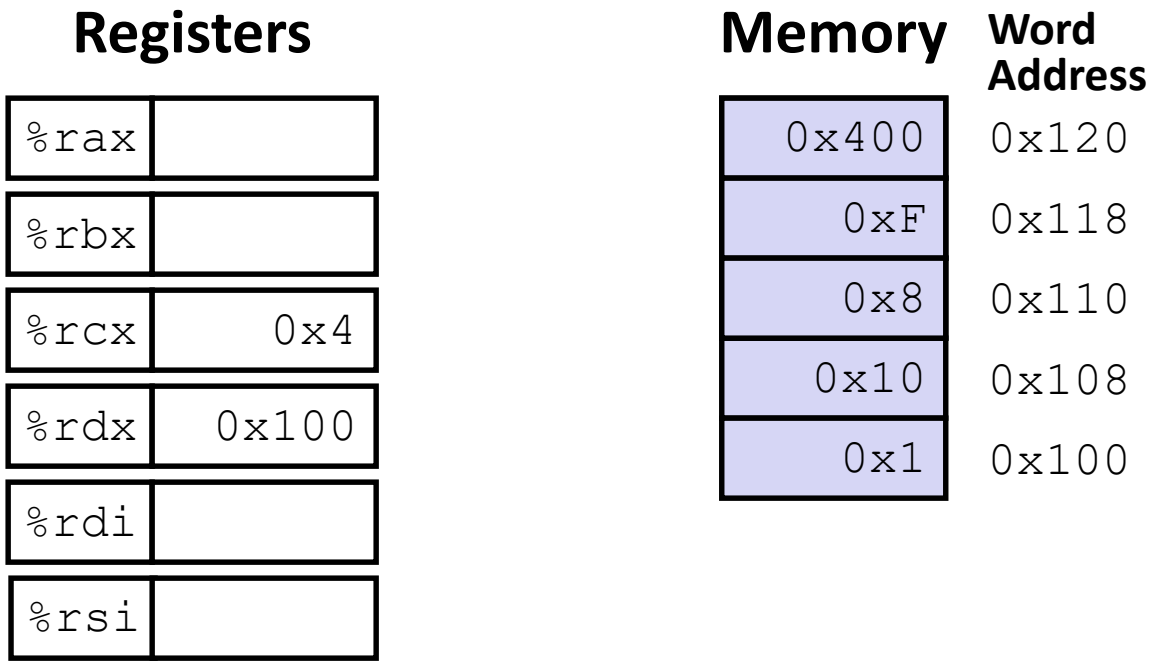
  D. `movq (%rdi,%rdi,8), %rax`

- If %rsi is 0x B0BACAFE 1EE7 F0 0D, what is its value after executing **`movswl %si, %esi`**?

Address Computation Instruction

- `leaq src, dst`
  - "`lea`" stands for *load effective address*
  - `src` is address expression (any of the formats we've seen)
  - `dst` is a register
  - Sets `dst` to the *address* computed by the `src` expression (does not go to memory! – it just does math)
  - Example: `leaq (%rdx,%rcx,4), %rax`
- Uses:
  - Computing addresses without a memory reference
    - *e.g.* translation of `p = &x[i];`
  - Computing arithmetic expressions of the form `x+k*i+d`
    - Though `k` can only be 1, 2, 4, or 8

Example: `lea` vs. `mov`




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

`lea` – "It just does math"

Arithmetic Example

```
long arith(long x, long y, long z)
{
  long t1 = x + y;
  long t2 = z + t1;
  long t3 = x + 4;
  long t4 = y * 48;
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

```
arith:
  leaq    (%rdi,%rsi), %rax
  addq    %rdx, %rax
  leaq    (%rsi,%rsi,2), %rdx
  salq    $4, %rdx
  leaq    4(%rdi,%rdx), %rcx
  imulq   %rcx, %rax
  ret
```

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rdx	3rd argument (z)

- Interesting Instructions
  - leaq: "address" computation
  - salq: shift
  - imulq: multiplication
    - Only used once!

Arithmetic Example

```
long arith(long x, long y, long z)
{
  long t1 = x + y;
  long t2 = z + t1;
  long t3 = x + 4;
  long t4 = y * 48;
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

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

```
arith:
  leaq    (%rdi,%rsi), %rax    # rax/t1    = x + y
  addq    %rdx, %rax           # rax/t2    = t1 + z
  leaq    (%rsi,%rsi,2), %rdx  # rdx       = 3 * y
  salq    $4, %rdx             # rdx/t4    = (3*y) * 16
  leaq    4(%rdi,%rdx), %rcx   # rcx/t5    = x + t4 + 4
  imulq   %rcx, %rax           # rax/rval = t5 * t2
  ret
```

Control Flow

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rax	return value

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

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

Control Flow

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rax	return value

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

Conditional jump

Unconditional jump

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

Conditionals and Control Flow

- Conditional branch/*jump*
  - Jump to somewhere else if some *condition* is true, otherwise execute next instruction
- Unconditional branch/*jump*
  - *Always* jump when you get to this instruction

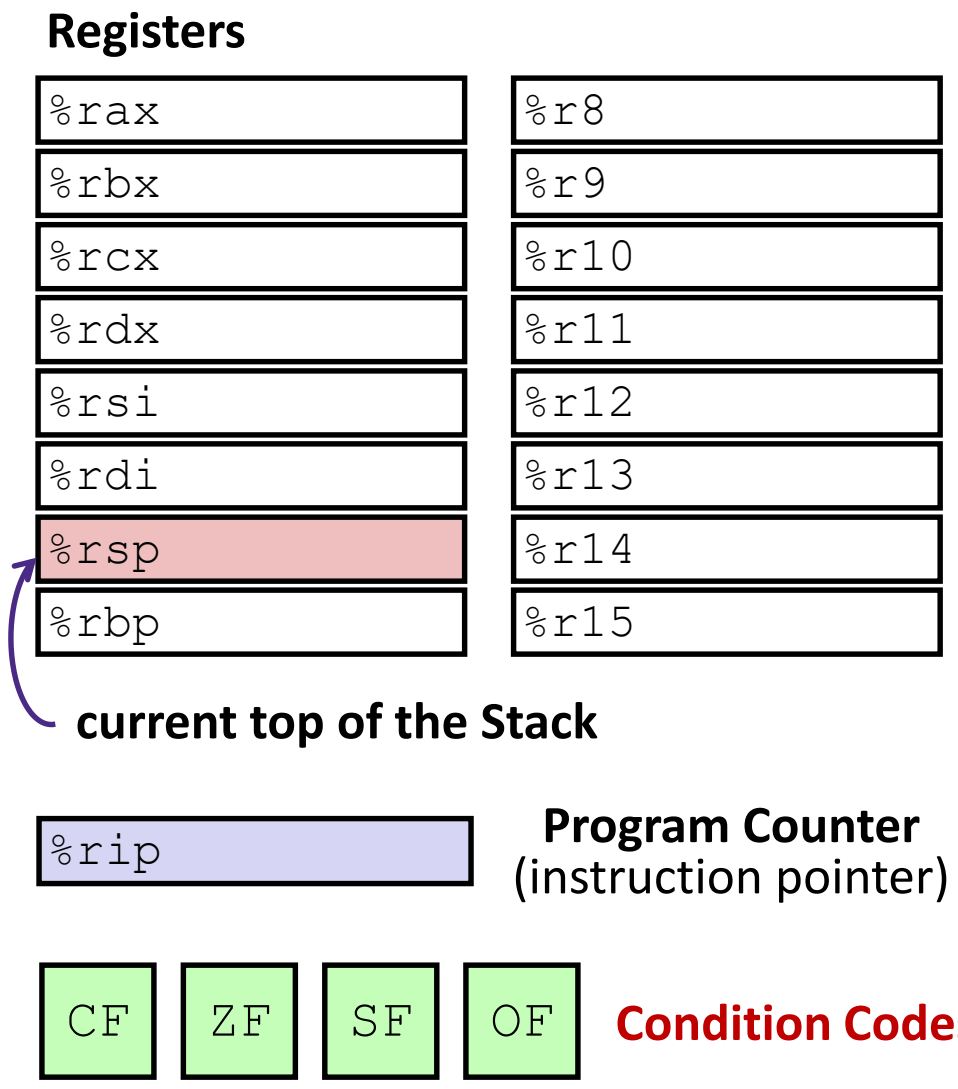
- Together, they can implement most control flow constructs in high-level languages:
  - **`if`** (*condition*) **`then`** {…} **`else`** {…}
  - **`while`** (*condition*) {…}
  - **`do`** {…} **`while`** (*condition*)
  - **`for`** (*initialization*`;` *condition*`;` *iterative*) {…}
  - **`switch`**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

x86 Control Flow

- **Condition codes**
- **Conditional and unconditional branches**
- Loops
- Switches

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`**)
    - Single bit registers:



Condition Codes (Implicit Setting)

- *Implicitly* set by **arithmetic** operations
  - (think of it as side effects)
  - Example: **`addq`** `src, dst` ↔ `r = d+s`

  - **`CF=1`** if carry out from MSB (*unsigned* overflow)
  - **`ZF=1`** if `r==0`
  - **`SF=1`** if `r<0` (if MSB is 1)
  - **`OF=1`** if *signed* overflow

    `(s>0 && d>0 && r<0)||(s<0 && d<0 && r>=0)`
  - *Not* set by `lea` instruction (beware!)

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

Condition Codes (Explicit Setting: Compare)

- *Explicitly* set by **Compare** instruction
  - **`cmpq`** `src1, src2`
  - **`cmpq`** `a, b` sets flags based on `b-a`, but doesn't store

  - **`CF=1`** if carry out from MSB (good for *unsigned* comparison)
  - **`ZF=1`** if `a==b`
  - **`SF=1`** if `(b-a)<0` (if MSB is 1)
  - **`OF=1`** if *signed* overflow

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

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

Condition Codes (Explicit Setting: Test)

- *Explicitly* set by **Test** instruction
  - **`testq`** `src2, src1`
  - **`testq`** `a, b` sets flags based on `a&b`, but doesn't store
    - Useful to have one of the operands be a ***mask***
  - Can't have carry out (**`CF`**) or overflow (**`OF`**)
  - **`ZF=1`** if `a&b==0`
  - **`SF=1`** if `a&b<0` (signed)

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

Example Condition Code Setting

- Assuming that %al = 0x80 and %bl = 0x81, which flags (CF, ZF, SF, OF) are set when we execute **`cmpb %al, %bl`**?

Using Condition Codes: Jumping

- `j*` Instructions
  - Jumps to ***target*** (an address) based on condition codes

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 “<“)

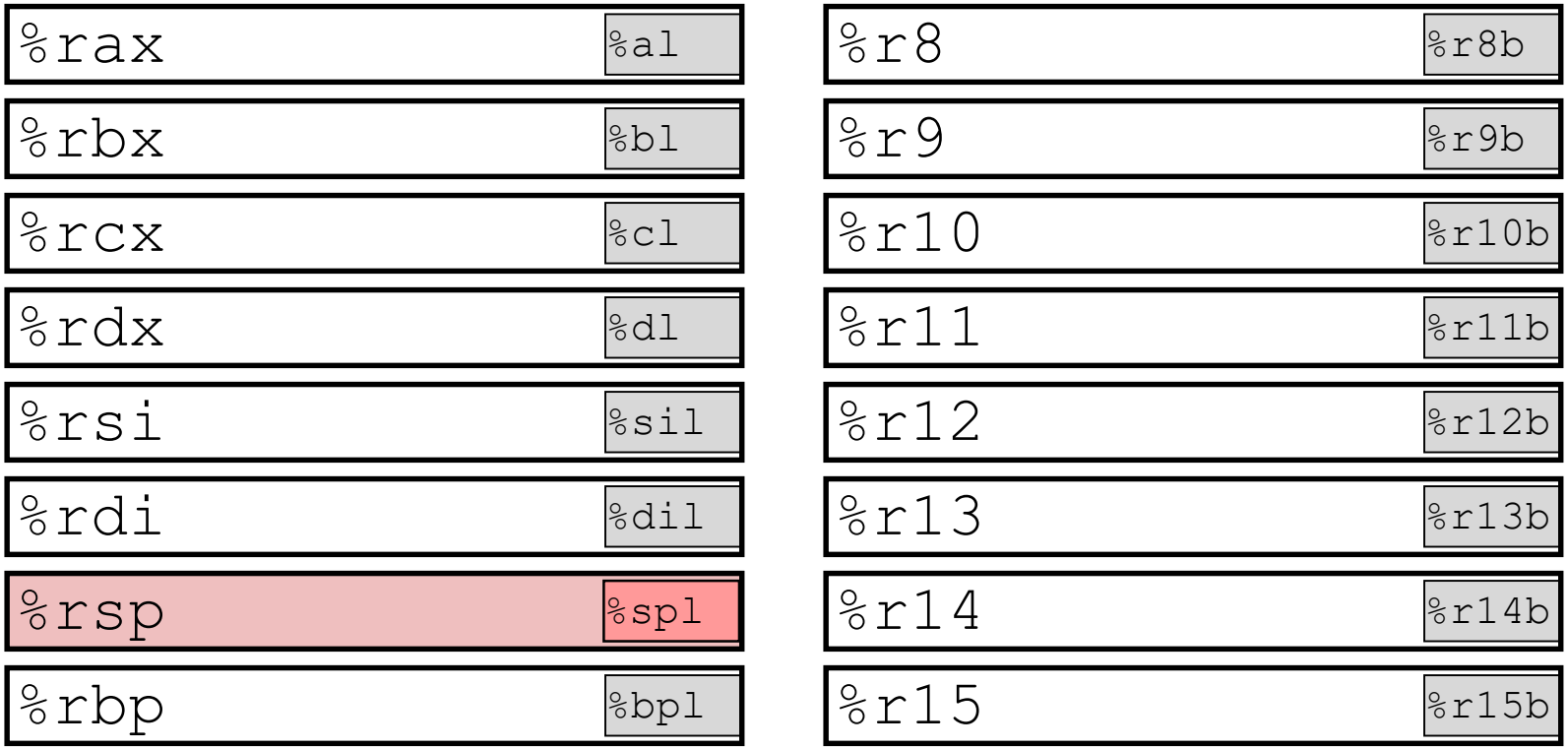
Using Condition Codes: Setting

- `set*` Instructions
  - Set low-order byte of `dst` to 0 or 1 based on condition codes
  - Does not alter remaining 7 bytes

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 “<”)

Reminder: x86-64 Integer Registers

- Accessing the low-order byte:



Reading Condition Codes

Register	Use(s)
%rdi	1st argument (x)
%rsi	2nd argument (y)
%rax	return value

- set* Instructions
  - Set a low-order byte to 0 or 1 based on condition codes
  - Operand is byte register (e.g. al, dl) or a byte in memory
  - Do not alter remaining bytes in register
    - Typically use movzbl (zero-extended mov) to finish job

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

```
cmpq    %rsi, %rdi    #
setg    %al           #
movzbl  %al, %eax     #
ret
```

Reading Condition Codes

Register	Use(s)
%rdi	1st argument (x)
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- set* Instructions
  - Set a low-order byte to 0 or 1 based on condition codes
  - Operand is byte register (e.g. al, dl) or a byte in memory
  - Do not alter remaining bytes in register
    - Typically use movzbl (zero-extended mov) to finish job

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

```
cmpq    %rsi, %rdi    # Compare x:y
setg    %al           # Set when >
movzbl  %al, %eax     # Zero rest of %rax
ret
```

Aside: `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`)

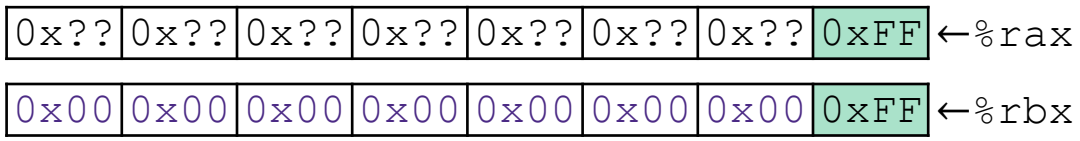
`movzSD` / `movsSD`:

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

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

Example:

```
movzbq %al, %rbx
```



Aside: `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)

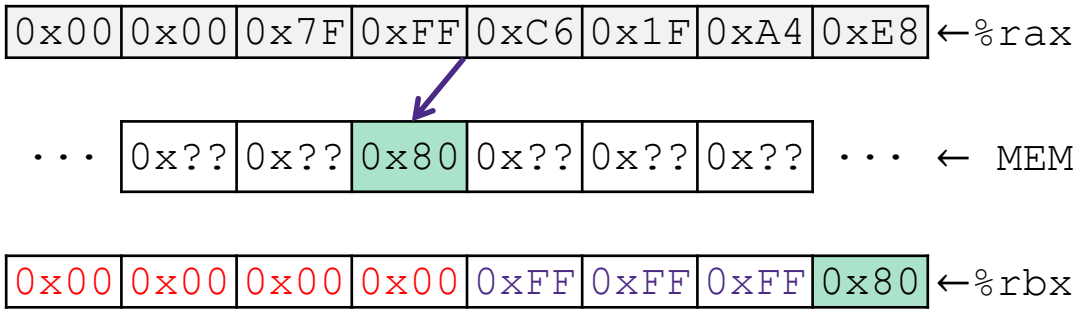
D – size of dest (**`w`** = 2 bytes, **`l`** = 4, **`q`** = 8)

Note: In x86-64, *any instruction* that generates a 32-bit (long word) value for a register also sets the high-order portion of the register to 0. Good example on p. 184 in the textbook.

Example:

```
movsbl (%rax), %ebx
```

Copy 1 byte from memory into 8-byte register & sign extend it



Summary

- Control flow in x86 determined by status of Condition Codes
  - Showed **C**arry, **Z**ero, **S**ign, and **O**verflow, though others exist
  - Set flags with arithmetic instructions (implicit) or Compare and Test (explicit)
  - Set instructions read out flag values
  - Jump instructions use flag values to determine next instruction to execute