x86 Programming II

CSE 351 Autumn 2016

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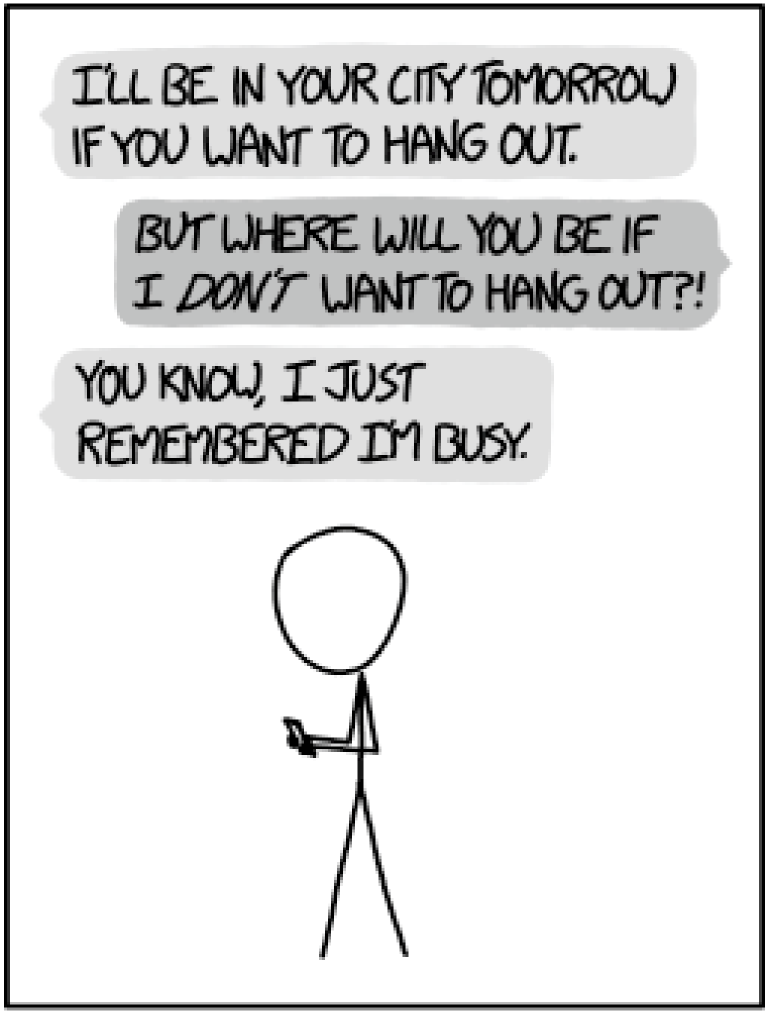


WHY I TRY NOT TO BE PEDANTIC ABOUT CONDITIONALS.

http://xkcd.com/1652/

Administrivia

- Lab 2 released tomorrow
  - Learn to use gdb and look at assembly code
- Homework 1 due on Friday (10/21)

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)

    D Rb Ri S
  - Example: `leaq (%rdx,%rcx,4), %rax`

    movq (%rdx,%rcx,4), %rax → p = x[i]
- Uses:
  - Computing addresses without a memory reference
    - e.g., translation of `p = &x[i];` lea (address-of)
  - Computing arithmetic expressions of the form `x+k*i`

    ← S
    - Though k can only be 1, 2, 4, or 8

Example: `lea` vs. `mov`

rax | eax | ax | al

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

Memory	Word Address
0x400	0x120
0xF	0x118
0x8	0x110
0x10	0x108
0x1	0x100

0x100 + 0x4 * 4 + 0 = 0x110

Reg[Rb] + Reg[Ri] * S + D

D Rb Ri S

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

Rb

→ 0x110 (addr)

→ 0x8 (data)

→ 0x100

→ 0x1

Example: `lea` vs. `mov` (solution)

Registers

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

Memory	Word Address
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
```

Arithmetic Example

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

```
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;
}
```

→ leaq + salq

addr = Reg[Rb]+Reg[Ri]*S + D

y + y *2 + 0 = 3y

```
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
```

x y → x+y

z → x+y+z

y y → 3y

→ 16*(3y) = 48y

x 48y → x+48y+4

→ (x+y+z)(x+48y+4)

- 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

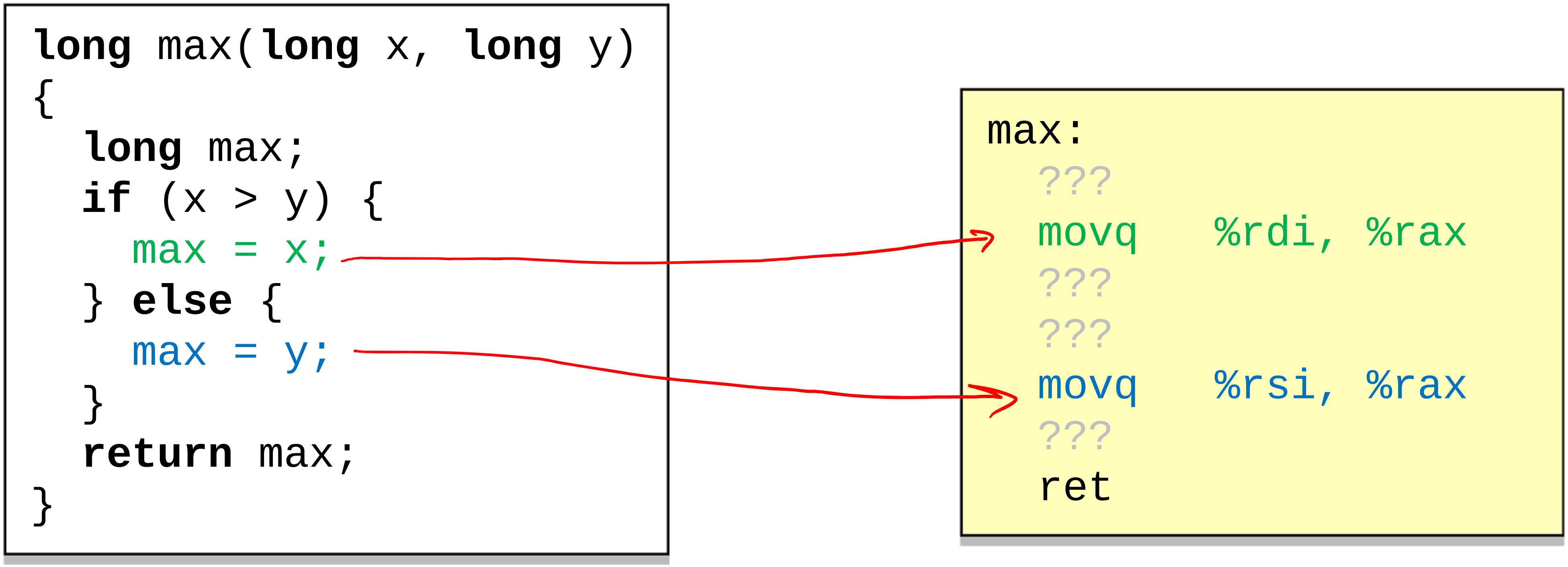
```
arith:
  leaq    (%rdi,%rsi), %rax    # rax/t1   = x + y
  addq    %rdx, %rax           # rax/t2   = t1 + z
  leaq    (%rsi,%rsi,2), %rdx  # rdx      = 3 * y
  salq    $4, %rdx             # rdx/t4   = (3*y) * 16
  leaq    4(%rdi,%rdx), %rcx   # rcx/t5   = x + t4 + 4
  imulq   %rcx, %rax        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

x86 Control Flow

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

Control Flow

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



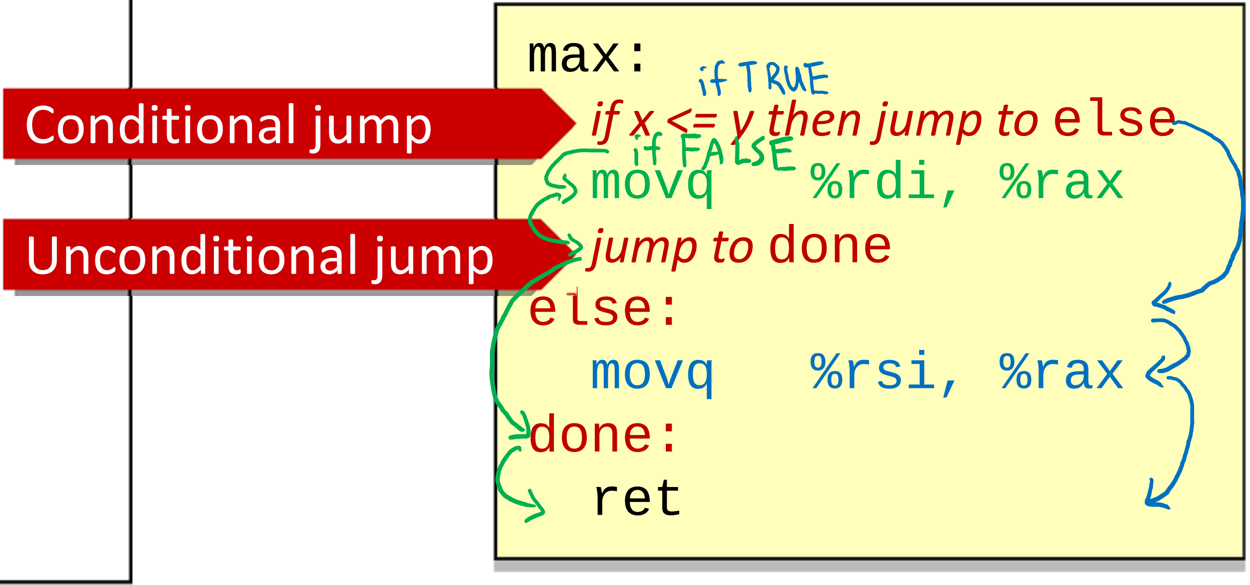
```
long max(long x, long y)
{
  long max;
  if (x > y) {
    max = x;
  } else {
    max = y;
  }
  return max;
}
```

```
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
```

if TRUE

if FALSE

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`** `{…}`

Jumping

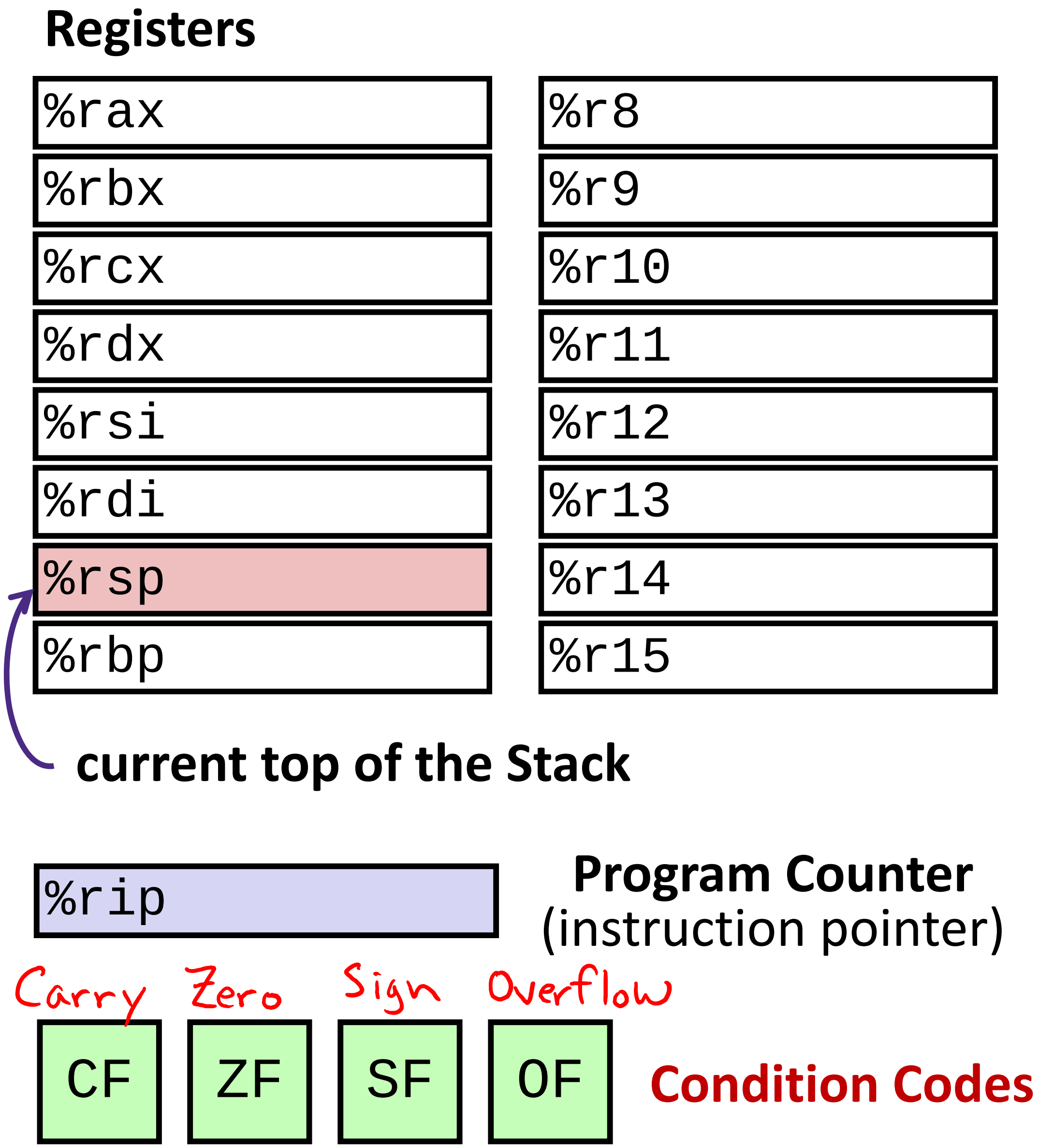
- `j*` Instructions
  - Jumps to ***target*** (argument – actually just an address)
  - Conditional jump relies on special *condition code registers*

Instruction	Condition	Description
`jmp` *target*	1	Unconditional ← special (no condition!)
`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)

don't sweat the details

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:



Registers

`%rax`	`%r8`
`%rbx`	`%r9`
`%rcx`	`%r10`
`%rdx`	`%r11`
`%rsi`	`%r12`
`%rdi`	`%r13`
`%rsp`	`%r14`
`%rbp`	`%r15`

current top of the Stack

`%rip`

Program Counter
(instruction pointer)

Carry Zero Sign Overflow

CF ZF SF OF

Condition Codes

Condition Codes (Implicit Setting)

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

  - **`CF=1`** if carry out from MSB (unsigned overflow)
  - **`ZF=1`** if `t==0`
  - **`SF=1`** if `t<0` (assuming signed, actually just if MSB is 1)
  - **`OF=1`** if two's complement (signed) overflow `(a>0 && b>0 && t<0)||(a<0 && b<0 && t>=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 src2, src1`

    b a a - b
  - `cmpq b, a` sets flags based on `a-b`, but doesn't store

  - **CF=1** if carry out from MSB (used for unsigned comparison)
  - **ZF=1** if `a==b`
  - **SF=1** if `(a-b)<0` (signed)
  - **OF=1** if two's complement (signed) overflow

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

ZF=1: if a&a == 0 → a == 0

SF=1: if a&a < 0 → a < 0

ZF	SF	a
0	0	a > 0
0	1	a < 0
1	0	a == 0
1	1	not possible

  - Example: `testq %rax, %rax`
    - Tells you if (+), 0, or (−) based on ZF and SF

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

Reading Condition Codes

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

stores logical result of condition (1=True, 0=False)

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 "<")

same instruction endings as j* and condition statements

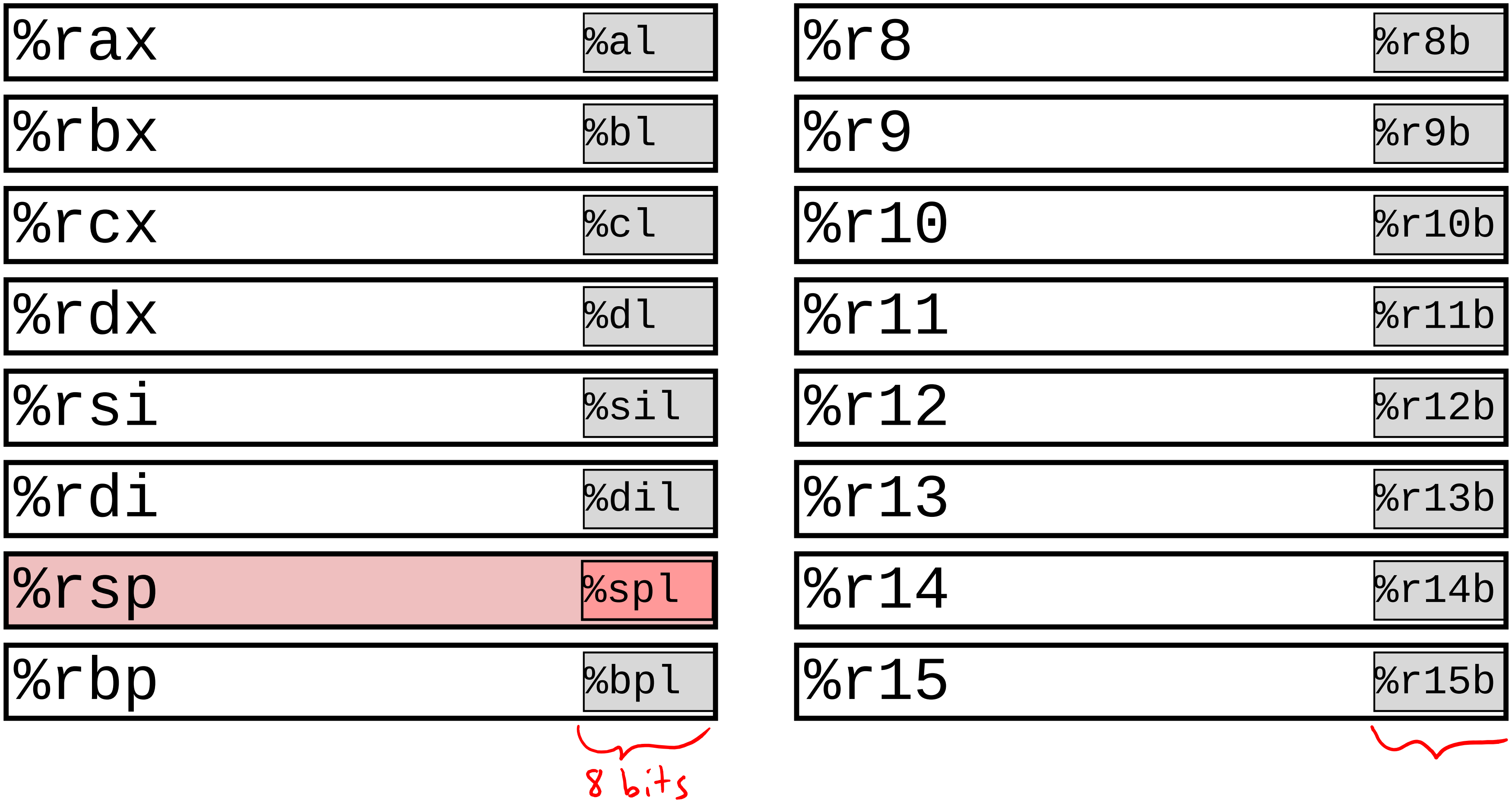
same flag

x86-64 Integer Registers

- Accessing the low-order byte:

l for "low-order byte"

"b" for byte



%rax	%al	%r8	%r8b
%rbx	%bl	%r9	%r9b
%rcx	%cl	%r10	%r10b
%rdx	%dl	%r11	%r11b
%rsi	%sil	%r12	%r12b
%rdi	%dil	%r13	%r13b
%rsp	%spl	%r14	%r14b
%rbp	%bpl	%r15	%r15b

8 bits

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;
}
```

```
               y        x
cmpq    %rsi, %rdi    #  x-y
setg    %al           #  %al = (x>y)
     greater than
movzbl  %al, %eax     #  %rax = (x>y)
ret
```

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   # 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)

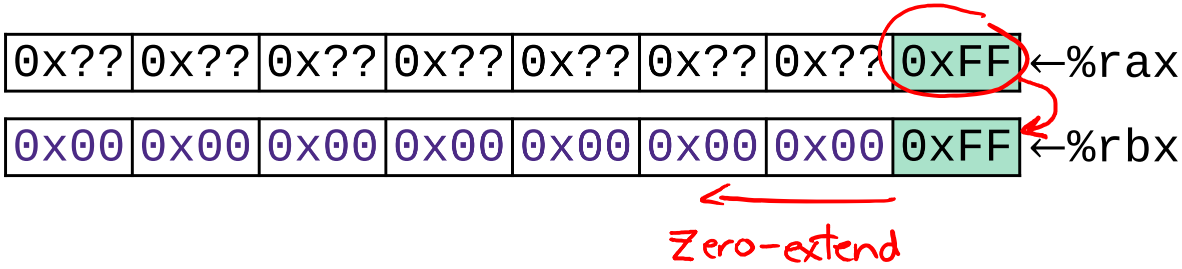
D – size of dest (**`w`** = 2 bytes, **`l`** = 4, **`q`** = 8)

Example:

1 byte

`movzbq %al, %rbx`

8 bytes



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)

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.

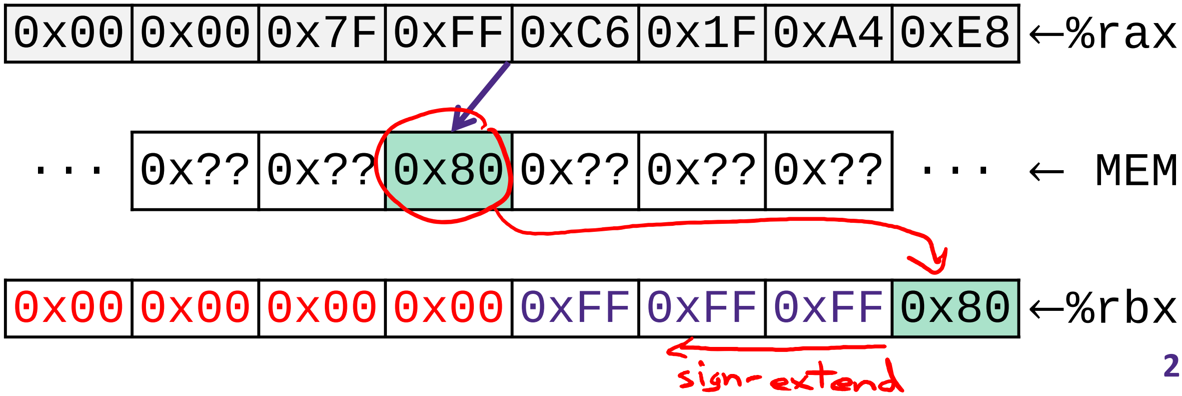
Example:

1 byte

`movsbl (%rax), %ebx`

4 bytes

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


0x00 0x00 0x7F 0xFF 0xC6 0x1F 0xA4 0xE8 ←%rax

... 0x?? 0x?? 0x80 0x?? 0x?? 0x?? ... ← MEM

0x00 0x00 0x00 0x00 0xFF 0xFF 0xFF 0x80 ←%rbx

sign-extend

Choosing instructions for conditionals

replace "j" with "set" to get other instructions

		`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`	

Typically come in pairs:

① test or compare

② jump or set

```
      cmp 5,(p)
je:   *p == 5
jne:  *p != 5
jg:   *p >  5
jl:   *p <  5
```

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

`test a,0x1`

je: $a_{LSB} == 0$

jne: $a_{LSB} == 1$

Choosing instructions for conditionals

		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	

Register	**Use(s)**
%rdi	argument x
%rsi	argument y
%rax	return value

```
if (x < 3) {
  return 1;
}
return 2;
```

```
  cmpq $3, %rdi
  jge T2
T1: # x < 3:
  movq $1, %rax
  ret
T2: # !(x < 3):
  movq $2, %rax
  ret
```

x≥3

cmpq $3, %rdi
jge T2

label
(addr)

Your Turn!

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

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

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

- Can view in provided `control.s`
  - `gcc –Og -S –fno-if-conversion control.c`

Your Turn! (solution)

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

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

- Can view in provided `control.s`
  - `gcc –Og -S –fno-if-conversion control.c`

Choosing instructions for conditionals

		cmp b,a	**test a,b**
je	"Equal"	② a == b	③ 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"	① a < b	a&b < 0
jle	"Less or equal"	a <= b	a&b <= 0
ja	"Above" (unsigned >)	a > b	
jb	"Below" (unsigned <)	a < b	

%al & %bl == 0 when either %al or %bl is false

↑ this is the else case!

```
if (x < 3 && x == y) {
  return 1;
} else {
  return 2;
}
```

```
  cmpq $3, %rdi
  setl %al

  cmpq %rsi, %rdi
  sete %bl

  testb %al, %bl
  je T2
T1: # x < 3 && x == y:
  movq $1, %rax
  ret
T2: # else
  movq $2, %rax
  ret
```

① cmpq $3, %rdi / setl %al } %al = (x<3)

② cmpq %rsi, %rdi / sete %bl } %bl=(x==y)

③ testb %al, %bl / je T2 ← jump to T2 if (%al & %bl)==0

Summary

- `lea` is address calculation instruction
  - Does NOT actually go to memory
  - Used to compute addresses or some arithmetic expressions
- 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