Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

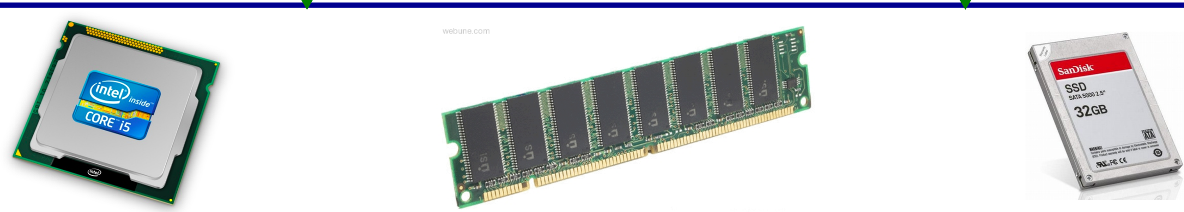
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Computer system:



Memory & data
Integers & floats
Machine code & C
x86 assembly
Procedures & stacks
Arrays & structs
Memory & caches
Processes
Virtual memory
Memory allocation
Java vs. C

Next x86 topics

- x86 basics: registers
- Move instructions, registers, and operands
- Arithmetic operations
- Memory addressing modes
- `swap` example

What Is A Register (again)?

- **A location in the CPU that stores a small amount of data, which can be accessed very quickly** (once every clock cycle)

- **Registers have *names*, not *addresses***
  - In assembly, they start with `%` (e.g. `%rsi`)

- **Registers are at the heart of assembly programming**
  - They are a precious commodity in all architectures, but *especially* x86

x86-64 Integer Registers – 64 bits wide

%rax	%eax	%r8	%r8d
%rbx	%ebx	%r9	%r9d
%rcx	%ecx	%r10	%r10d
%rdx	%edx	%r11	%r11d
%rsi	%esi	%r12	%r12d
%rdi	%edi	%r13	%r13d
%rsp	%esp	%r14	%r14d
%rbp	%ebp	%r15	%r15d

- Can reference low-order 4 bytes (also low-order 1 & 2 bytes)

Some History: IA32 Registers – 32 bits wide

	32-bit	16-bit virtual registers (backwards compatibility)			Name Origin (mostly obsolete)
general purpose	%eax	%ax	%ah	%al	*accumulate*
general purpose	%ecx	%cx	%ch	%cl	*counter*
general purpose	%edx	%dx	%dh	%dl	*data*
general purpose	%ebx	%bx	%bh	%bl	*base*
general purpose	%esi	%si			*source index*
general purpose	%edi	%di			*destination index*
	%esp	%sp			***stack pointer***
	%ebp	%bp			***base pointer***

16-bit virtual registers (backwards compatibility)

Name Origin (mostly obsolete)

Assembly Data Types

- **"Integer" data of 1, 2, 4, or 8 bytes**
  - Data values
  - Addresses (untyped pointers)
- **Floating point data of 4, 8, 10 or 2x8 or 4x4 or 8x2**
  - Different registers for those (e.g. `%xmm1`, `%ymm2`)
  - Come from *extensions to x86* (SSE, AVX, …)
  - Probably won't have time to get into these ☹
- **No aggregate types such as arrays or structures**
  - Just contiguously allocated bytes in memory

Two common syntaxes

- "AT&T": used by our course, slides, textbook, gnu tools, …
- "Intel": used by Intel documentation, Intel tools, …
- Must know which you're reading

Three Basic Kinds of Instructions

- **Transfer data between memory and register**
  - *Load* data from memory into register
    - %reg = Mem[address]
  - *Store* register data into memory
    - Mem[address] = %reg

Remember: memory is indexed just like an array[] of bytes!

- **Perform arithmetic function on register or memory data**
  - `c = a + b;`   `z = x << y;`   `i = h & g;`
- **Control flow: what instruction to execute next**
  - Unconditional jumps to/from procedures
  - Conditional branches

Operand types

- ***Immediate:*** **Constant integer data**
  - Example: `$0x400`, `$-533`
  - Like C literal, but prefixed with **‘$’**
  - Encoded with 1, 2, 4, or 8 bytes *depending on the instruction*
- ***Register:*** **One of 16 integer registers**
  - Example: `%rax`, `%r13`
  - But `%rsp` reserved for special use
  - Others have special uses for particular instructions
- ***Memory:*** **Consecutive bytes of memory at a given/computed address**
  - Simplest example: `(%rax)`
  - Various other “address modes”

`%rax`
`%rcx`
`%rdx`
`%rbx`
`%rsi`
`%rdi`
`%rsp`
`%rbp`
`%rN`

Moving Data

- **Moving Data**
  - `mov_` ***Source*, *Dest***
  - `_` is one of {`b`, `w`, `l`, `q`}
    - Determines size of operands!

  - **`movq` *Source*, *Dest*:** %rax
    Move 8-byte "quad word"
  - **`movl` *Source*, *Dest*:**
    Move 4-byte "long word"
  - **`movw` *Source*, *Dest*:**
    Move 2-byte "word"
  - **`movb` *Source*, *Dest*:**
    Move 1-byte "byte"

**confusing historical terms…
not the current machine word size**

- **Lots of these in typical code**

movq Operand Combinations

$0x4

	Source	Dest	Src,Dest	C Analog
movq	*Imm*	*Reg*	`movq $0x4, %rax`	`var_a = 0x4;`
		Mem	`movq $-147, (%rax)`	`*p_a = -147;`
	Reg	*Reg*	`movq %rax, %rdx`	`var_d = var_a;`
		Mem	`movq %rax, (%rdx)`	`*p_d = var_a;`
	Mem	*Reg*	`movq (%rax), %rdx`	`var_d = *p_a;`

Cannot do memory-memory transfer with a single instruction

How would you do it?

Some Arithmetic Operations

Maximum of one memory operand.

- **Binary (two-operand) Instructions:**

Format	Computation	
`addq` *Src, Dest*	*Dest = Dest + Src*	(*Dest* += *Src*)
`subq` *Src, Dest*	*Dest = Dest – Src*	
`imulq` *Src, Dest*	*Dest = Dest * Src*	
`sarq` *Src, Dest*	*Dest = Dest >> Src*	***Arithmetic***
`shrq` *Src, Dest*	*Dest = Dest >> Src*	***Logical***
`shlq` *Src, Dest*	*Dest = Dest << Src*	(also called `salq`)
`xorq` *Src, Dest*	*Dest = Dest ^ Src*	
`andq` *Src, Dest*	*Dest = Dest & Src*	
`orq` *Src, Dest*	*Dest = Dest | Src*	

- **Watch out for argument order! (especially `subq`)**
- **No distinction between signed and unsigned int (why?)**
  - except arithmetic vs. logical shift right
- **How do you implement, "r3 = r1 + r2"?**

mov r1, r3
add r2, r3

Some Arithmetic Operations

- **One Operand (Unary) Instructions**

`incq` *Dest*	*Dest* = *Dest* + 1	increment
`decq` *Dest*	*Dest* = *Dest* – 1	decrement
`negq` *Dest*	*Dest* = –*Dest*	*negate*
`notq` *Dest*	*Dest* = ~*Dest*	*bitwise complement*

- **See textbook section 3.5.5 for more instructions: `mulq`, `cqto`, `idivq`, `divq`**

Arithmetic Example

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

```
long simple_arith(long x, long y)
{
  long t1 = x + y;
  long t2 = t1 * 3;
  return t2;
}
```

```
  y += x;
  y *= 3;
  long r = y;
  return r;
```

```
simple_arith:
  addq    %rdi, %rsi
  imulq   $3, %rsi
  movq    %rdi, %rax
  ret
```

Memory vs. registers

- **What is the main difference?**
  - Addresses vs. Names
  - Big vs. Small
  - Slow vs. Fast
  - Dynamic vs. Static

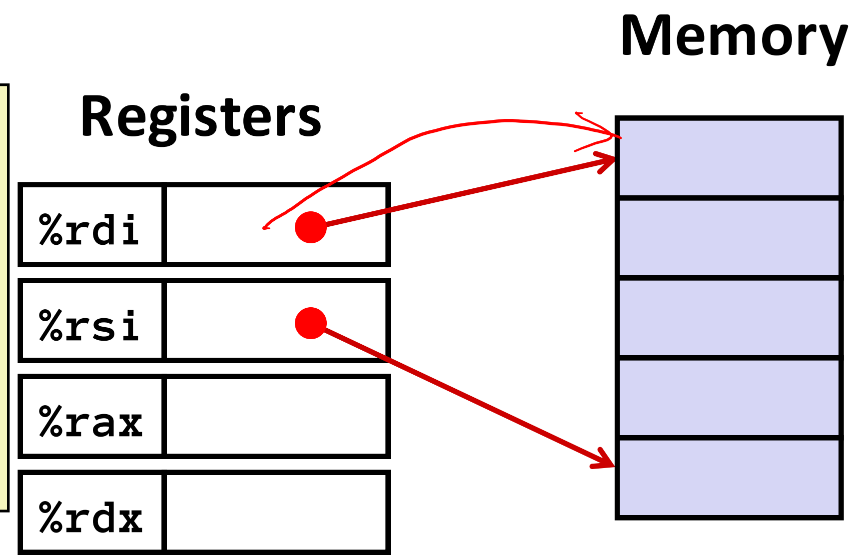
Example of Basic Addressing Modes

```
void swap(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

```
swap:
   movq    (%rdi), %rax
   movq    (%rsi), %rdx
   movq    %rdx, (%rdi)
   movq    %rax, (%rsi)
   ret
```

Understanding Swap()

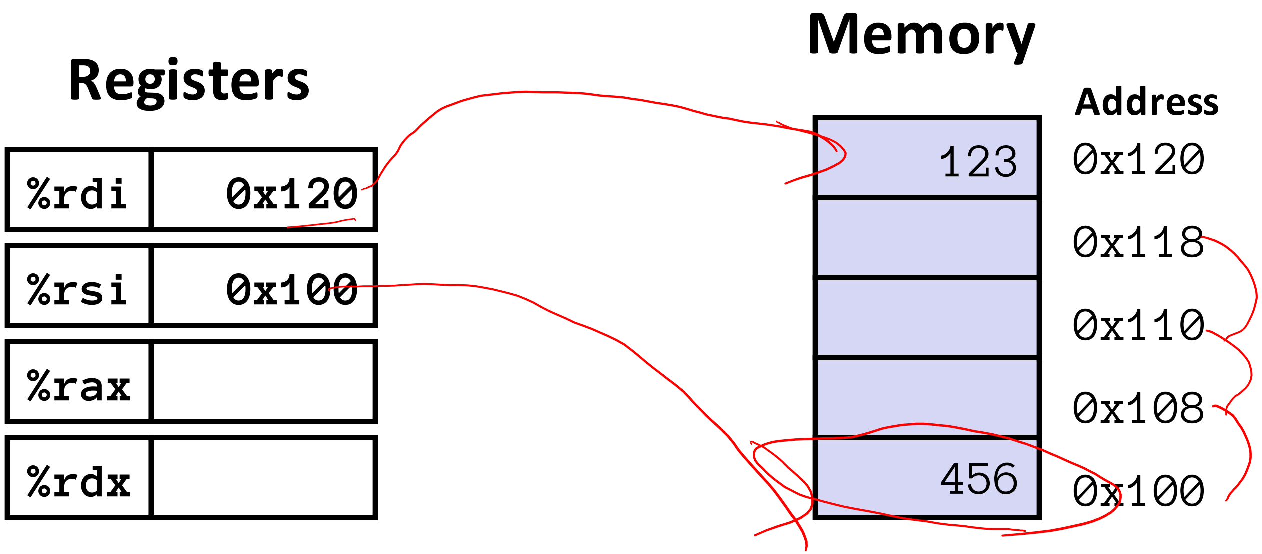
```
void swap(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```



Register		Variable
%rdi	⇔	xp
%rsi	⇔	yp
%rax	⇔	t0
%rdx	⇔	t1

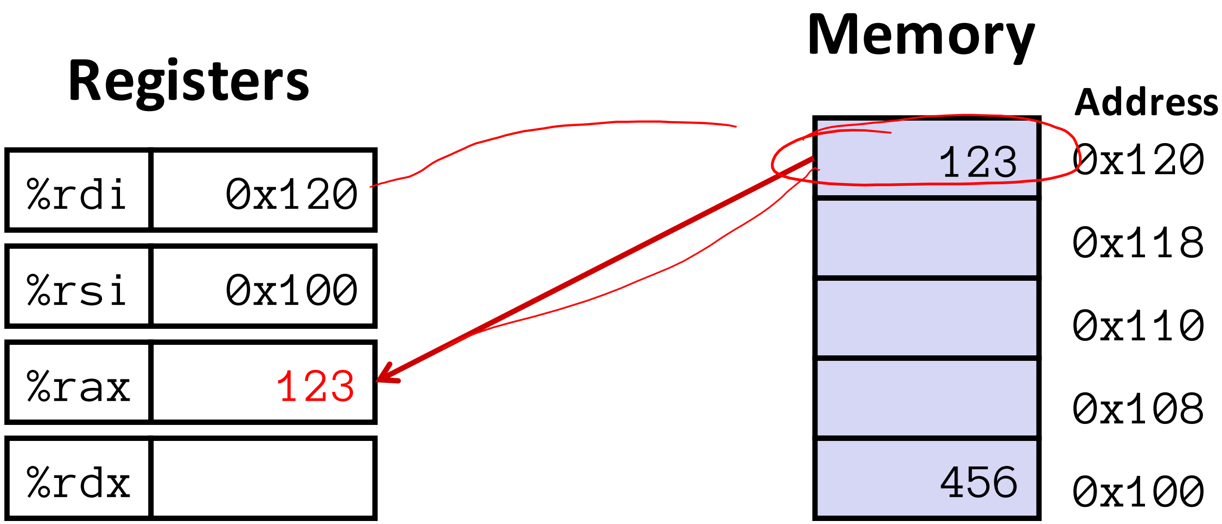
```
swap:
    movq    (%rdi), %rax   # t0 = *xp
    movq    (%rsi), %rdx   # t1 = *yp
    movq    %rdx, (%rdi)   # *xp = t1
    movq    %rax, (%rsi)   # *yp = t0
    ret
```

Understanding Swap()



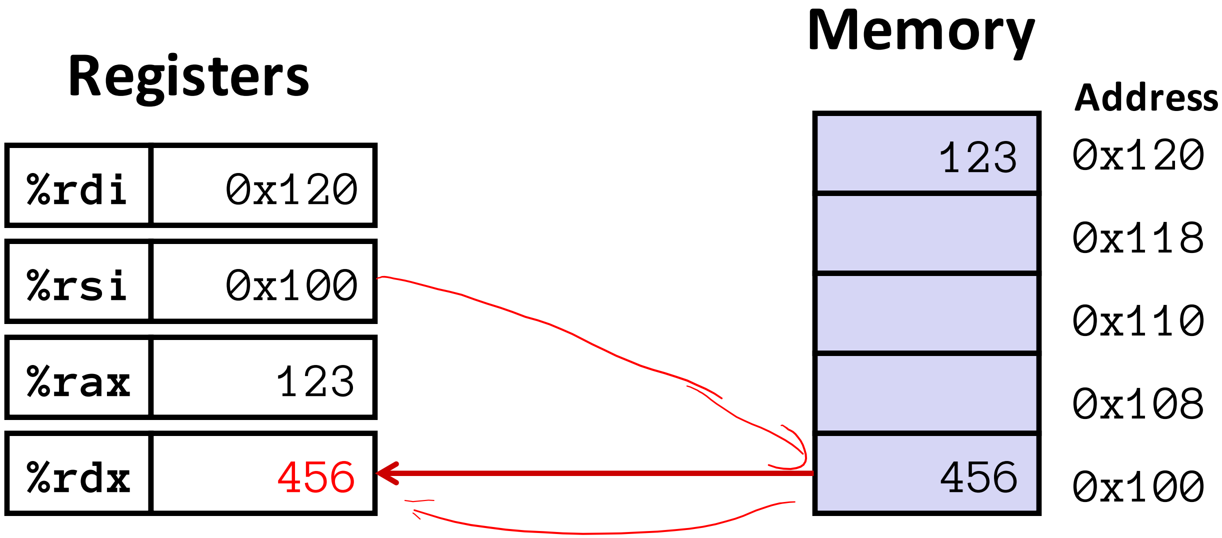

```
swap:
    movq     (%rdi), %rax    # t0 = *xp
    movq     (%rsi), %rdx    # t1 = *yp
    movq     %rdx, (%rdi)    # *xp = t1
    movq     %rax, (%rsi)    # *yp = t0
    ret
```

Understanding Swap()



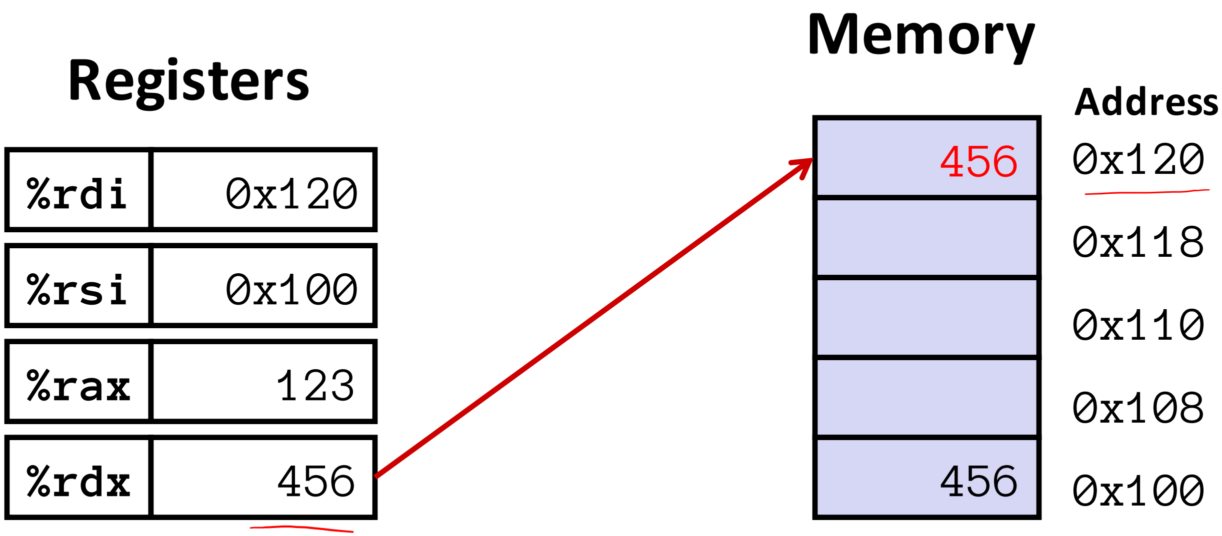

```
swap:
    movq    (%rdi), %rax   # t0 = *xp
    movq    (%rsi), %rdx   # t1 = *yp
    movq    %rdx, (%rdi)   # *xp = t1
    movq    %rax, (%rsi)   # *yp = t0
    ret
```

Understanding Swap()



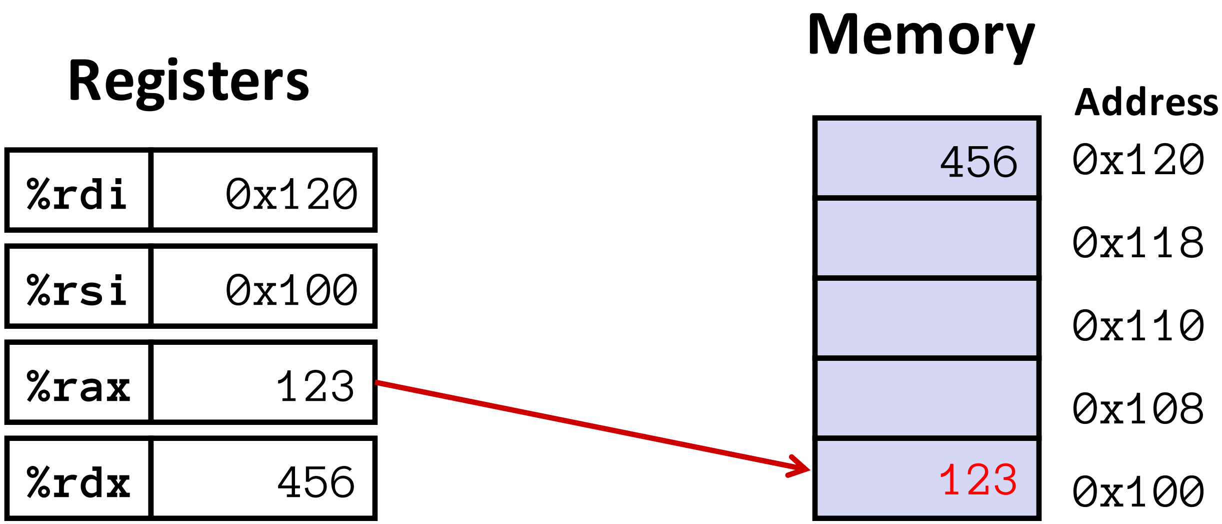

```
swap:
    movq    (%rdi), %rax   # t0 = *xp
    movq    (%rsi), %rdx   # t1 = *yp
    movq    %rdx, (%rdi)   # *xp = t1
    movq    %rax, (%rsi)   # *yp = t0
    ret
```

Understanding Swap()




```
swap:
    movq    (%rdi), %rax   # t0 = *xp
    movq    (%rsi), %rdx   # t1 = *yp
    movq    %rdx, (%rdi)   # *xp = t1
    movq    %rax, (%rsi)   # *yp = t0
    ret
```

Understanding Swap()




```
swap:
    movq    (%rdi), %rax   # t0 = *xp
    movq    (%rsi), %rdx   # t1 = *yp
    movq    %rdx, (%rdi)   # *xp = t1
    movq    %rax, (%rsi)   # *yp = t0
    ret
```

Memory Addressing Modes: Basic

- **Indirect** `(R)` `Mem[R]`
  - Register R specifies the memory address
  - Aha! Pointer dereferencing in C

```
movq (%rcx), %rax
```

- **Displacement** `D(R)` `Mem[R+D]`
  - Register R specifies a memory address
    - (e.g. the start of some memory region)
  - Constant displacement D specifies the offset from that address

```
movq 8(%rbp), %rdx
```

Complete Memory Addressing Modes

- **Remember, the addresses used for accessing memory in `mov` (and other) instructions can be computed in several different ways**
- **Most General Form:**

`D(Rb,Ri,S)` `Mem[Rb + Ri*S + D]`

  - `Rb`: Base register: Any of the 16 integer registers
  - `Ri`: Index register: Any, except for **`%rsp`**
  - `S`: Scale: 1, 2, 4, or 8 (*why these numbers?*)
  - `D`: Constant "displacement" value represented in 1, 2, or 4 bytes
- **Special Cases: can use any combination of `D`, `Rb`, `Ri` and `S`**

`(Rb,Ri)`	`Mem[Rb + Ri]`	`(S=1, D=0)`
`D(Rb,Ri)`	`Mem[Rb + Ri + D]`	`(S=1)`
`(Rb,Ri,S)`	`Mem[Rb + Ri*S]`	`(D=0)`

(, %rsp, ?)

Address Computation Examples

%rdx	0xf000
%rcx	0x0100

(Rb,Ri)	Mem[Rb + Ri]
D(,Ri,S)	Mem[Ri*S + D]
(Rb,Ri,S)	Mem[Rb + Ri*S]
D(Rb)	Mem[Rb + D]

Expression	Address Computation	Address
0x8(%rdx)	0x8 + 0xf000	0xf008
(%rdx,%rcx)	0xf000 + 0x0100	0xf100
(%rdx,%rcx,4)	0xf000 + 0x0100 * 4	~~0x~~ f400
0x80(,%rdx,2)	0xf000 * 2 + 0x80	0x1e080

Address Computation Examples

`%rdx`	`0xf000`
`%rcx`	`0x0100`

```
(Rb,Ri)     Mem[Rb + Ri]
D(,Ri,S)    Mem[Ri*S + D]
(Rb,Ri,S)   Mem[Rb + Ri*S]
D(Rb)       Mem[Rb + D]
```

Expression	Address Computation	Address
`0x8(%rdx)`	`0xf000 + 0x8`	`0xf008`
`(%rdx,%rcx)`	`0xf000 + 0x100`	`0xf100`
`(%rdx,%rcx,4)`	`0xf000 + 0x100*4`	`0xf400`
`0x80(,%rdx,2)`	`0xf000*2 + 0x80`	`0x1e080`

Address Computation Instruction

- `leaq` *Src*, *Dest*
  - *Src* is address expression (Any of the formats we just discussed!)
  - *Dest* is a register
  - Set *Dest* to address computed by expression
  - 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`
    - k = 1, 2, 4, or 8

The `leaq` Instruction

- **"lea" stands for *load effective address***
- Example: `leaq (%rdx,%rcx,4), %rax`

Does the `leaq` instruction go to memory? NO

"`leaq` – it just does math"

`leaq` vs. `movq` example

Registers

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

Memory

	Address
0x400	0x120
0xf	0x118
0x8	0x110
0x10	0x108
0x1	0x100

0x110 = 0x100 + 0x4 * 4

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

`leaq` vs. `movq` example (solution)

Registers

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

Memory

	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`	Argument **x**
`%rsi`	Argument **y**
`%rdx`	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;                12
  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
```

Interesting Instructions

- **`leaq`**: address computation
- **`salq`**: shift
- **`imulq`**: multiplication
  - But, only used once instead of twice

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`	Argument **`x`**
`%rsi`	Argument **`y`**
`%rdx`	Argument **`z`**
`%rax`	`t1, t2, rval`
`%rdx`	`t4`
`%rcx`	`t5`

Topics: control flow

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

Control Flow

Register	Use(s)
%rdi	Argument x
%rsi	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	Argument x
%rsi	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`** {…}

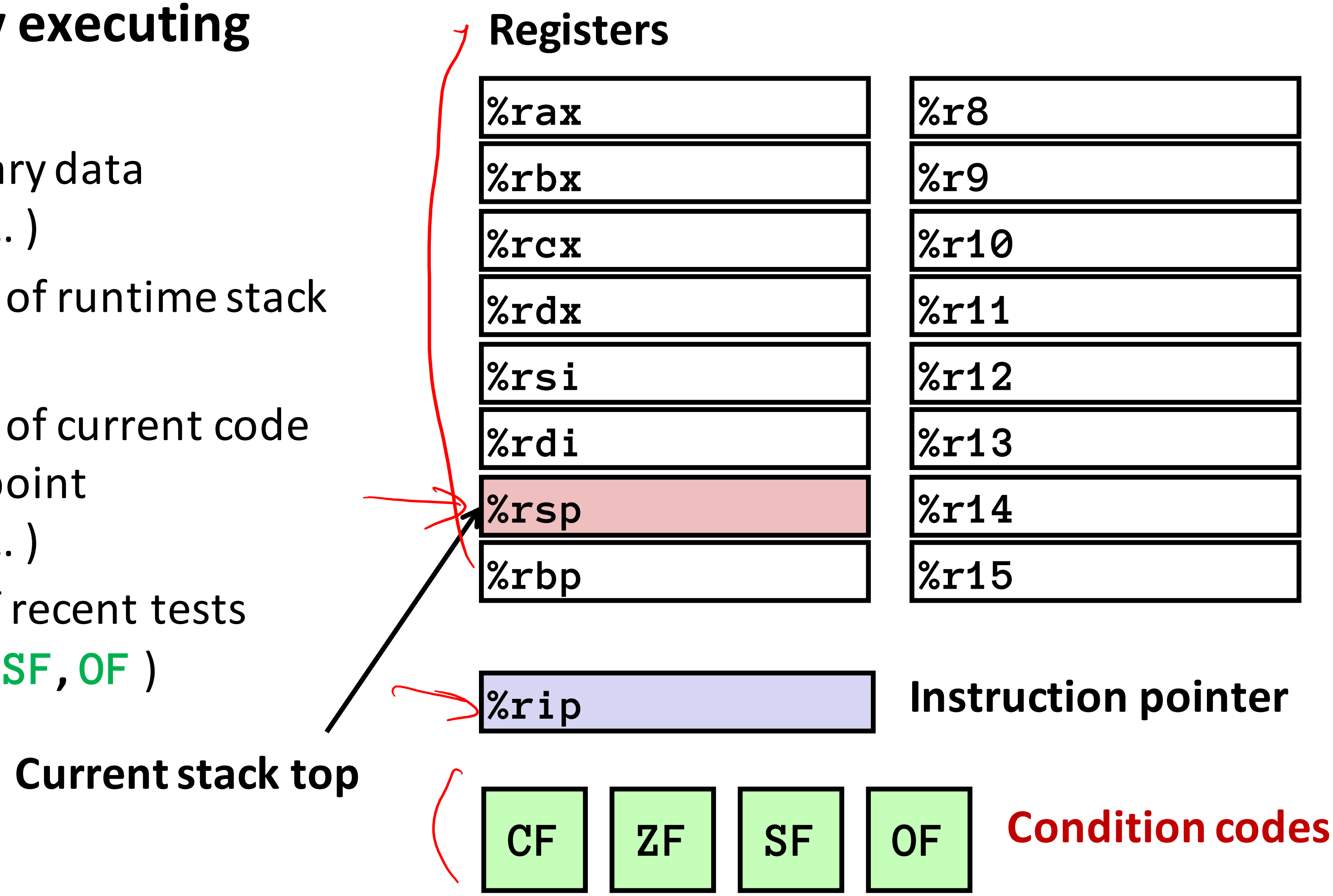
Jumping

- `j_` **Instructions**
  - Only takes ***jump target*** as argument (actually just an address)
  - Conditional jump relies on special *condition code registers*
    - *Splits conditional branches into 2 (or more) instructions*

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)

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)

- **Condition codes: single bit registers**

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

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

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

  - **CF = 1** if carry out from most significant bit (unsigned overflow)
  - **ZF = 1** if `t == 0`
  - **SF = 1** if `t < 0` (assuming signed, actually just if MSB is 1)
  - **OF = 1** if twos-complement (signed) overflow
    `(a>0 && b>0 && t<0) || (a<0 && b<0 && t>=0)`

Not set by `lea` instruction (beware!)

Condition Codes (Explicit Setting: Compare)

- **Explicit Setting by Compare Instruction**

  `cmpq` *Src2,Src1*   > < <=

  `cmpq b,a` like computing `a-b` without setting destination

  - **CF = 1** if carry out from most significant bit (used for unsigned comparisons)
  - **ZF = 1** if `a == b`
  - **SF = 1** if `(a-b) < 0` (as signed)
  - **OF = 1** if twos 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)

- **Explicit Setting by Test instruction**

  `testq` *Src2*, *Src1*

  `testq 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 = 1** if a&b `== 0`
- **SF = 1** if a&b `< 0`

$x > 0$

- `testq %rax, %rax`
  - Sets SF and ZF, check if rax is +,0,-

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 combinations of condition codes
  - Does not alter remaining 7 bytes

set_	Condition	Description
sete *Dest*	ZF	Equal / Zero
setne *Dest*	~ZF	Not Equal / Not Zero
sets *Dest*	SF	Negative
setns *Dest*	~SF	Nonnegative
setg *Dest*	~(SF^OF)&~ZF	Greater (Signed)
setge *Dest*	~(SF^OF)	Greater or Equal (Signed)
setl *Dest*	(SF^OF)	Less (Signed)
setle *Dest*	(SF^OF)|ZF	Less or Equal (Signed)
seta *Dest*	~CF&~ZF	Above (unsigned ">")
setb *Dest*	CF	Below (unsigned "<")

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

x86-64 Integer Registers

%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

- Can reference low-order byte

Aside: `movz` and `movs` examples

`movz__` *Src, RegisterDest* *Move with zero extension*

`movs__` *Src, RegisterDest* *Move with sign extension*

- Use when copying a *smaller* source value to a *larger* destination
- Source can be memory or register; Destination must be a register
- Fills remaining bytes of dest with **zeroes** (`movz`) or by **sign extension** (`movs`)

`movzSD` / `movsSD`:

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

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.

Examples:

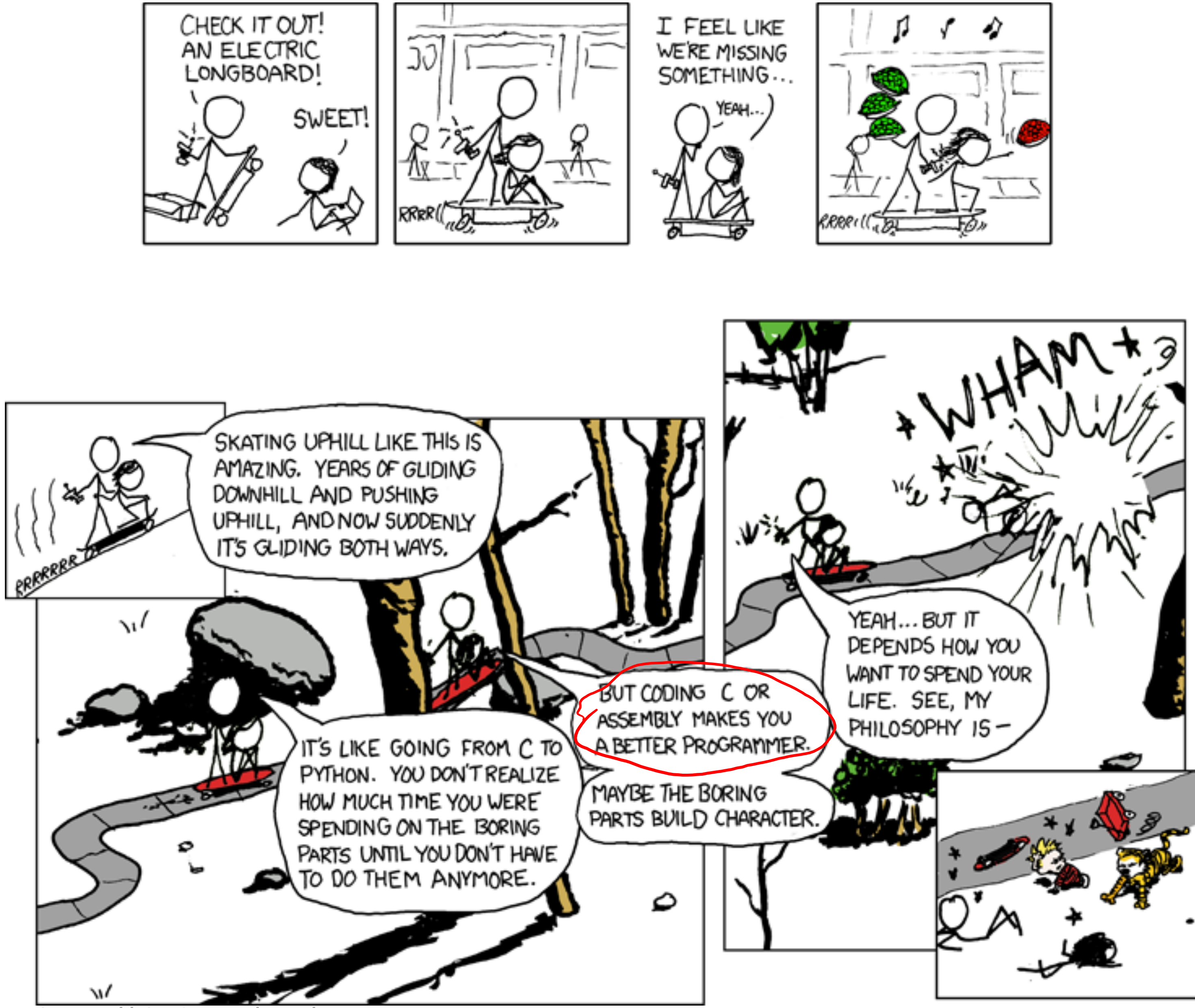
`movzbq %al, %rbx`

							0xFF	←%rax
0x00	0x00	0x00	0x00	0x00	0x00	0x00	0xFF	←%rbx

`movsbl (%rax), %rbx`

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

April 18



https://xkcd.com/409/

Reading Condition Codes (Cont.)

- **set_ Instructions:**
  - Set single byte to 0 or 1 based on combination of condition codes
  - Operand is one of the byte registers (eg. al, dl) or a byte in memory
- **set instructions do not alter remaining bytes in register**
  - Typically use `movzbl` to finish job
    - "zero-extended" move, sets upper bytes to 0

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

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

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

What does each of these instructions do?

Reading Condition Codes (Cont.)

- **set_ Instructions:**
  - Set single byte to 0 or 1 based on combination of condition codes
  - Operand is one of the byte registers (eg. al, dl) or a byte in memory
- **set instructions do not alter remaining bytes in register**
  - Typically use movzbl to finish job
    - "zero-extended" move, sets upper bytes to 0

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

```
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
```

Choosing instructions for conditionals

Set

		`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`	

```
     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	

```
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
```

if x>=3

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

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 && 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
```

if (x<3) {
  if (x==y) {
    ret 1

Conditional Branch Example (with Jumps)

- **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:
                              # x > y:
    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 Branch Example (with Jumps)

- **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
                         # x > y:
    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

Expressing with Goto Code

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

```
long absdiff_j(long x, long y)
{
    long result;
    int ntest = x <= y;
    if (ntest) goto Else;
    result = x-y;
    goto Done;
 Else:
    result = y-x;
 Done:
    return result;
}
```

- C allows "**goto**" as means of transferring control
  - Closer to machine-level programming style
- Generally considered bad coding style

Conditional Move

Bonus Content
(nonessential)
more details at end of slides

- **Conditional Move Instructions**
  - `cmovC` src, dest
  - Move value from src to dest if condition *C* holds
  - `if` (*Test*) *Dest* ← *Src*
  - GCC tries to use them (but, only when known to be **safe**)
- **Why is this useful?**
  - Branches are very disruptive to instruction flow through pipelines
  - Conditional moves do not require control transfer

```
long absdiff(long x, long y)
{
  return x>y ? x-y : y-x;
}
```

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

Compiling Loops

C/Java code:

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

Machine code:

```
loopTop:    testq %rax, %rax
            je    loopDone
            <loop body code>
            jmp   loopTop
loopDone:
```

- **How to compile other loops basically similar**
  - Will show variations and complications in coming slides, but likely to skip all the details in class…
- **Most important to consider:**
  - When should conditionals be evaluated? (*while* vs. *do-while*)
  - How much jumping is involved?

Compiling Loops

While loop

C/Java code:

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

Machine code:

```
loopTop:    testq %rax, %rax
            je    loopDone
            <loop body code>
            jmp   loopTop
loopDone:
```

Do-while loop

C/Java code:

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

Machine code:

```
loopTop:
            <loop body code>
            testq  %rax, %rax
            jne    loopTop
loopDone:
```

Do-While Loop Example

Detailed Walkthrough
(skipping in class)

C Code

```
long pcount_do(unsigned long x)
{
  long result = 0;
  do {
    result += x & 0x1;
    x >>= 1;
  } while (x);
  return result;
}
```

Goto Version

```
long pcount_goto(unsigned long x)
{
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if(x) goto loop;
  return result;
}
```

- Count number of 1's in argument **x** ("popcount")
- Use backward branch to continue looping
- Only take branch when "while" condition holds

Detailed Walkthrough
(skipping in class)

Do-While Loop Compilation

Goto Version

```
long pcount_goto(unsigned long x) {
  long result = 0;
 loop:
  result += x & 0x1;
  x >>= 1;
  if (x) goto loop;
  return result;
}
```

Register	Use(s)
%rdi	Argument x
%rax	result

```
    movl    $0, %eax      # result = 0
.L2:                      # loop:
    movq    %rdi, %rdx
    andl    $1, %edx      #  t = x & 0x1
    addq    %rdx, %rax    #  result += t
    shrq    %rdi          #  x >>= 1
    jne     .L2           #  if (x) goto loop
    rep; ret              # return (rep weird)
```

General Do-While Loop 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

Detailed Walkthrough
(skipping in class)

General While Loop - Translation #1

- "Jump-to-middle" translation
- Used with –Og

While version

```
while (Test)
  Body
```

Goto Version

```
  goto test;
loop:
  Body
test:
  if (Test)
    goto loop;
done:
```

Detailed Walkthrough
(skipping in class)

While Loop Example – Translation #1

C Code

```
long pcount_while
  (unsigned long x)
{
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Jump to Middle

```
long pcount_goto_jtm
  (unsigned long x)
{
  long result = 0;
  goto test;
 loop:
  result += x & 0x1;
  x >>= 1;
 test:
  if (x) goto loop;
  return result;
}
```

- Used with –Og
- Compare to do-while version of function
- Initial goto starts loop at test

Detailed Walkthrough
(skipping in class)

General While Loop - Translation #2

While version

```
while (Test)
  Body
```

- "Do-while" conversion
- Used with –O1

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:
```

Detailed Walkthrough
(skipping in class)

While Loop Example – Translation #2

C Code

```
long pcount_while
  (unsigned long x)
{
  long result = 0;
  while (x) {
    result += x & 0x1;
    x >>= 1;
  }
  return result;
}
```

Do-While Version

```
long pcount_goto_dw
  (unsigned long x)
{
  long result = 0;
  if (!x) goto done;
loop:
  result += x & 0x1;
  x >>= 1;
  if (x) goto loop;
done:
  return result;
}
```

- **Used with –O1**
- **Compare to do-while version of function (one less jump?)**
- **Initial conditional guards entrance to loop**

Detailed Walkthrough
(skipping in class)

For Loop Form

General Form

```
for ( Init; Test; Update )

    Body
```

```
#define WSIZE 8*sizeof(int)
long pcount_for
  (unsigned long x)
{
  size_t i;
  long result = 0;
  for (i = 0; i < WSIZE; i++) {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
  }
  return result;
}
```

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned bit =
     (x >> i) & 0x1;
  result += bit;
}
```

Detailed Walkthrough
(skipping in class)

For Loop → While Loop

For Version

```
for (Init; Test; Update )
    Body
```

While Version

```
Init;
while (Test ) {
    Body
    Update;
}
```

Caveat:

- *C and Java have* `break` *and* `continue`
- *Conversion works fine for* `break`
- *But not* `continue`*: would skip doing Update, which it should do with for-loops*
- *Need* `goto` *to fix this*
- *Slides ignore this detail; textbook gets it right*

For Loop-While Conversion

Init

```
i = 0
```

Test

```
i < WSIZE
```

Update

```
i++
```

Body

```
{
  unsigned bit = (x >> i) & 0x1;
  result += bit;
}
```

```
long pcount_for_while(unsigned long x)
{
  size_t i;
  long result = 0;
  i = 0;
  while (i < WSIZE) {
    unsigned bit = (x >> i) & 0x1;
    result += bit;
    i++;
  }
  return result;
}
```

Detailed Walkthrough
(skipping in class)

For Loop Do-While Conversion

C Code

```
long pcount_for
  (unsigned long x)
{
  size_t i;
  long result = 0;
  for (i = 0; i < WSIZE; i++)
  {
    unsigned bit =
      (x >> i) & 0x1;
    result += bit;
  }
  return result;
}
```

- **Initial test can be optimized away**

Goto Version

```
long pcount_for_goto_dw
  (unsigned long x)
{
  size_t i;
  long result = 0;
  i = 0;                      Init
  if (!(i < WSIZE))           !Test
    goto done;
 loop:
  {
    unsigned bit =
      (x >> i) & 0x1;         Body
    result += bit;
  }
  i++;                        Update
  if (i < WSIZE)              Test
    goto loop;
 done:
  return result;
}
```

```
long switch_eg
   (long x, long y, long z)
{
    long w = 1;
    switch (x) {
    case 1:
        w = y*z;
        break;
    case 2:
        w = y/z;
        /* Fall Through */
    case 3:
        w += z;
        break;
    case 5:
    case 6:
        w -= z;
        break;
    default:
        w = 2;
    }
    return w;
}
```

Switch Statement Example

- **Multiple case labels**
  - Here: 5 & 6
- **Fall through cases**
  - Here: 2
- **Missing cases**
  - Here: 4

- **Implemented with:**
  - *Jump table*
  - *Indirect jump instruction*

Jump Table Structure

Switch Form

```
switch (x) {
  case val_0:
    Block 0
  case val_1:
    Block 1
    • • •
  case val_n-1:
    Block n–1
}
```

Jump Table

Jtab:

Targ0
Targ1
Targ2
• • •
Targn-1

Jump Targets

Targ0: **Code Block 0**

Targ1: **Code Block 1**

Targ2: **Code Block 2**

•
•
•

Targn-1: **Code Block *n*–1**

Approximate Translation

```
target = JTab[x];
goto target;
```

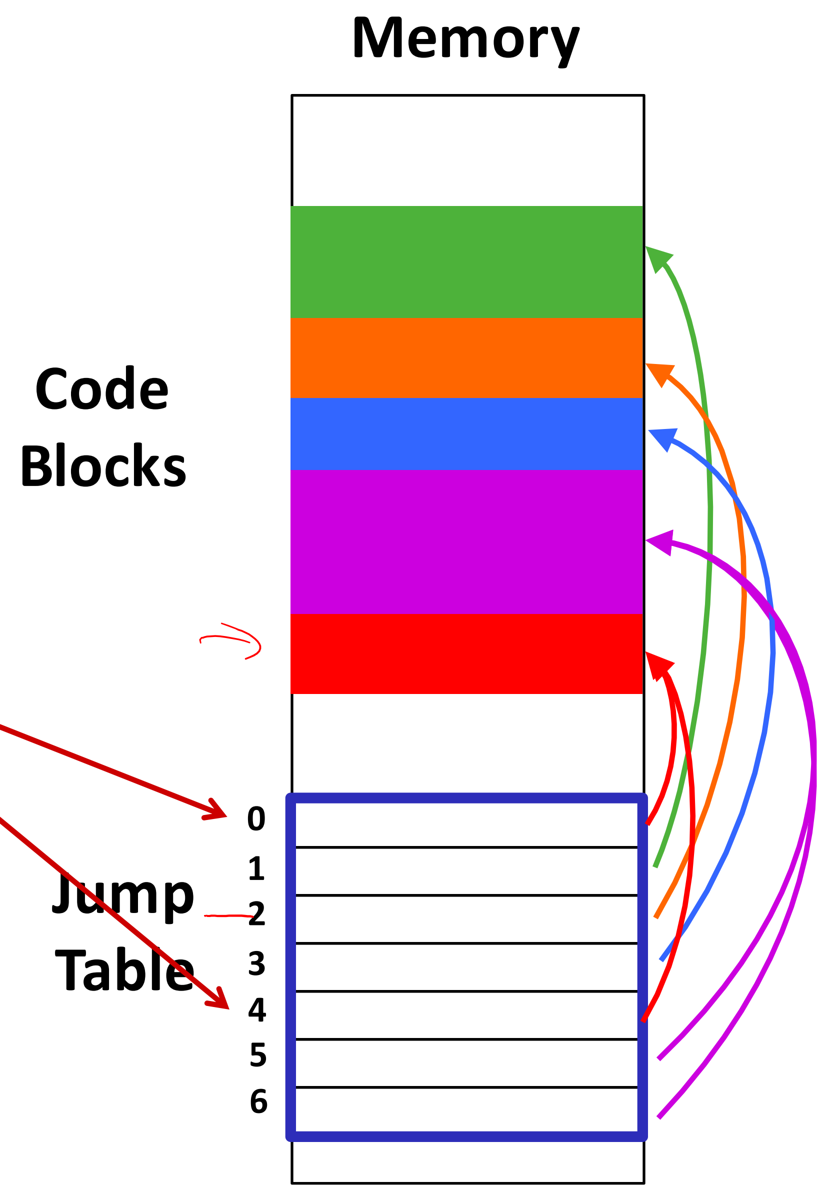
Jump Table Structure

C code:

```
switch (x) {
  case 1: <some code>
          break;
  case 2: <some code>
  case 3: <some code>
          break;
  case 5:
  case 6: <some code>
          break;
  default: <some code>
}
```

We can use the jump table when x <= 6:

```
if (x <= 6)
  target = JTab[x];
  goto target;
else
  goto default;
```



Switch Statement Example

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch (x) {
      . . .
    }
.L8
    return w;
}
```

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi     # x:6
    ja      .L8
    jmp     *.L4(,%rdi,8)
```

What range of values takes default?

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

Note compiler chose to not initialize w here

Switch Statement Example

```
long switch_eg(long x, long y, long z)
{
    long w = 1;
    switch (x) {
        . . .
    }
    return w;
}
```

Jump table

```
.section     .rodata
  .align 8
.L4:
  .quad      .L8   # x = 0
  .quad      .L3   # x = 1
  .quad      .L5   # x = 2
  .quad      .L9   # x = 3
  .quad      .L8   # x = 4
  .quad      .L7   # x = 5
  .quad      .L7   # x = 6
```

jump above (like jg, but unsigned)

```
switch_eg:
    movq    %rdx, %rcx
    cmpq    $6, %rdi    # x:6
    ja      .L8
    jmp     *.L4(,%rdi,8)
```

Indirect jump

Assembly Setup Explanation

- **Table Structure**
  - Each target requires 8 bytes
  - Base address at `.L4`

Jump table

```
.section    .rodata
  .align 8
.L4:
  .quad     .L8    # x = 0
  .quad     .L3    # x = 1
  .quad     .L5    # x = 2
  .quad     .L9    # x = 3
  .quad     .L8    # x = 4
  .quad     .L7    # x = 5
  .quad     .L7    # x = 6
```

- **Jumping**
  - **Direct:** `jmp .L8`
  - Jump target is denoted by label `.L8`
  - **Indirect:** `jmp *.L4(,%rdi,8)`
  - Start of jump table: `.L4`
  - Must scale by factor of 8 (addresses are 8 bytes)
  - Fetch target from effective Address `.L4 + x*8`
    - Only for $0 \le x \le 6$

Jump Table

declaring data, not instructions

8-byte memory alignment

Jump table

```
.section  .rodata
  .align 8
.L4:
  .quad   .L8  # x = 0
  .quad   .L3  # x = 1
  .quad   .L5  # x = 2
  .quad   .L9  # x = 3
  .quad   .L8  # x = 4
  .quad   .L7  # x = 5
  .quad   .L7  # x = 6
```

```
switch(x) {
case 1:        // .L3
    w = y*z;
    break;
case 2:        // .L5
    w = y/z;
    /* Fall Through */
case 3:        // .L9
    w += z;
    break;
case 5:
case 6:        // .L7
    w -= z;
    break;
default:       // .L8
    w = 2;
}
```

Code Blocks (x == 1)

```
switch(x) {
case 1:   // .L3
    w = y*z;
    break;
  . . .
}
```

```
.L3:
   movq    %rsi, %rax  # y
   imulq   %rdx, %rax  # y*z
   ret
```

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

Handling Fall-Through

```
long w = 1;
    . . .
switch (x) {
    . . .
case 2:    // .L5
    w = y/z;
    /* Fall Through */
case 3:    // .L9
    w += z;
    break;
    . . .
}
```

```
case 2:
    w = y/z;
    goto merge;
```

```
case 3:
        w = 1;
merge:
        w += z;
```

More complicated choice than "just fall-through" forced by "migration" of

w = 1;

- *Example compilation trade-off*

Code Blocks (x == 2, x == 3)

```
long w = 1;
      . . .
switch (x) {
      . . .
case 2:       // .L5
    w = y/z;
    /* Fall Through */
case 3:       // .L9
    w += z;
    break;
   . . .
}
```

```
.L5:                          # Case 2
   movq     %rsi, %rax  #  y in rax
   cqto                         #  Div prep
   idivq    %rcx           #  y/z
   jmp      .L6            #  goto merge
.L9:                          # Case 3
   movl     $1, %eax      #  w = 1
.L6:                          # merge:
   addq     %rcx, %rax  #  w += z
   ret
```

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

Code Blocks (x == 5, x == 6, default)

```
switch (x) {
  . . .
case 5:  // .L7
case 6:  // .L7
    w -= z;
    break;
default: // .L8
    w = 2;
}
```

```
.L7:                    # Case 5,6
  movl   $1, %eax       #  w = 1
  subq   %rdx, %rax     #  w -= z
  ret
.L8:                    # Default:
  movl   $2, %eax       #  2
  ret
```

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

Question

- **Would you implement this with a jump table?**

```
switch (x) {
  case 0:      <some code>
               break;
  case 10:     <some code>
               break;
  case 52000:  <some code>
               break;
  default:     <some code>
               break;
}
```

- **Probably not:**
  - Don’t want a jump table with 52001 entries for only 4 cases (too big)
  - about 200KB = 200,000 bytes
  - text of this switch statement = about 200 bytes

Bonus Content (nonessential)

Conditional Operator with Jumps

C Code

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

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

Example:

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

Goto Version

```
  ntest = !Test;
  if (ntest) goto Else;
  val = Then_Expr;
  goto Done;
Else:
  val = Else_Expr;
Done:
  . . .
```

- Ternary operator ?:
- *Test* is expression returning integer
  - = 0 interpreted as false
  - ≠ 0 interpreted as true
- Create separate code regions for then & else expressions
- Execute appropriate one

Bonus Content (nonessential)

Conditional Operator with Jumps

C Code

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

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

Example:

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

Goto Version

```
   ntest = !Test;
   if (ntest) goto Else;
   val = Then_Expr;
   goto Done;
Else:
   val = Else_Expr;
Done:
   . . .
```

- Ternary operator ?:
- *Test* is expression returning integer
  - = 0 interpreted as false
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- Create separate code regions for then & else expressions
- Execute appropriate one

Bonus Content (nonessential)

Using Conditional Moves

- **Conditional Move Instructions**
  - **`cmovC`** src, dest
  - Move value from src to dest if condition *C* holds
  - Instruction supports:

    if (Test) Dest ← Src
  - Supported in post-1995 x86 processors
  - GCC tries to use them
    - But, only when known to be **safe**
- **Why is this useful?**
  - Branches are very disruptive to instruction flow through pipelines
  - Conditional moves do not require control transfer

C Code

```
val = Test
    ? Then_Expr
    : Else_Expr;
```

"Goto" Version

```
result = Then_Expr;
else_val = Else_Expr;
nt = !Test;
if (nt) result = else_val;
return result;
```

Conditional Move Example

Bonus Content (nonessential)

```
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    # else_val = y-x
   cmpq    %rsi, %rdi    # x:y
   cmovle  %rdx, %rax    # if <=, result = else_val
   ret
```

Bonus Content
(nonessential)

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