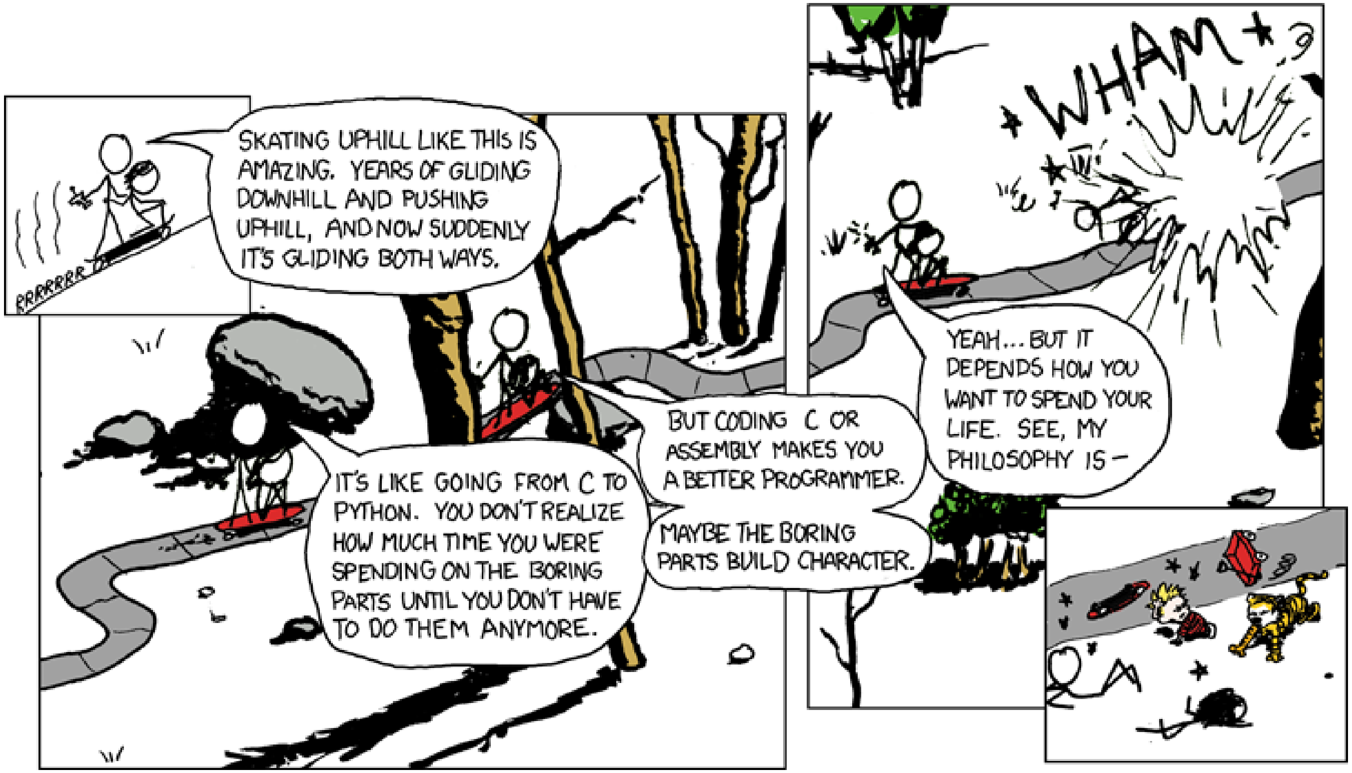
x86-64 Programming II

CSE 351 Spring 2018



http://xkcd.com/409/

Administrivia

- Lab 2 (x86-64) released today
  - Learn to read x86-64 assembly and use GDB
- Homework 2 due next week

- Midterm is in two weeks
  - More information soon

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:

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)

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` ↔ `r = d+s`
  - **CF=1** if carry out from MSB (unsigned overflow)
  - **ZF=1** if `r==0`
  - **SF=1** if `r<0` (assuming signed, actually just if MSB is 1)
  - **OF=1** if two's complement (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 (used for unsigned comparison)
  - **`ZF=1`** if `a==b`
  - **`SF=1`** if `(b-a)<0` (signed)
  - **`OF=1`** if two's complement (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)
  - 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*

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:

%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

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)
`%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:

`movzbq %al, %rbx`

0x??	0x??	0x??	0x??	0x??	0x??	0x??	0xFF	←%rax
0x00	0x00	0x00	0x00	0x00	0x00	0x00	0xFF	←%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

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

Choosing instructions for conditionals

- All arithmetic instructions set condition flags based on result of operation (op)
  - Conditionals are comparisons against 0
- Come in instruction *pairs*

```
      addq 5, (p)
je:    *p+5 == 0
jne:   *p+5 != 0
jg:    *p+5 >  0
jl:    *p+5 <  0
```

```
      orq a, b
je:    b|a == 0
jne:   b|a != 0
jg:    b|a >  0
jl:    b|a <  0
```

		(op) s, d
je	"Equal"	d (op) s == 0
jne	"Not equal"	d (op) s != 0
js	"Sign" (negative)	d (op) s < 0
jns	(non-negative)	d (op) s >= 0
jg	"Greater"	d (op) s > 0
jge	"Greater or equal"	d (op) s >= 0
jl	"Less"	d (op) s < 0
jle	"Less or equal"	d (op) s <= 0
ja	"Above" (unsigned >)	d (op) s > 0U
jb	"Below" (unsigned <)	d (op) s < 0U

Choosing instructions for conditionals

- Reminder: `cmp` is like `sub`, `test` is like `and`
  - Result is not stored anywhere

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

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

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

`testb a, 0x1`

`je:` a_{LSB} `== 0`

`jne:` a_{LSB} `== 1`

Choosing instructions for conditionals

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

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
```

Question

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

- **A.** `cmpq %rsi, %rdi`
`jle .L4`
- **B.** `cmpq %rsi, %rdi`
`jg .L4`
- **C.** `testq %rsi, %rdi`
`jle .L4`
- **D.** `testq %rsi, %rdi`
`jg .L4`
- **E.** We're lost…

Choosing instructions for conditionals

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

```
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
```

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