Assembly Programming III

CSE 351 Spring 2017

Guest Lecturer:

Justin Hsia

Instructor:

Ruth Anderson

Teaching Assistants:

Dylan Johnson

Kevin Bi

Linxing Preston Jiang

Cody Ohlsen

Yufang Sun

Joshua Curtis

Administrivia

- Lab 1 due TONIGHT, Friday (4/14)
  - Remember, you have *late days* available if needed.
- Homework 2 due next Wednesday (4/19)
- Lab 2 (x86-64) released soon!
  - Learn to read x86-64 assembly and use GDB

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

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

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** (`mov`**`z`**) or **sign bit** (`mov`**`s`**)

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

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

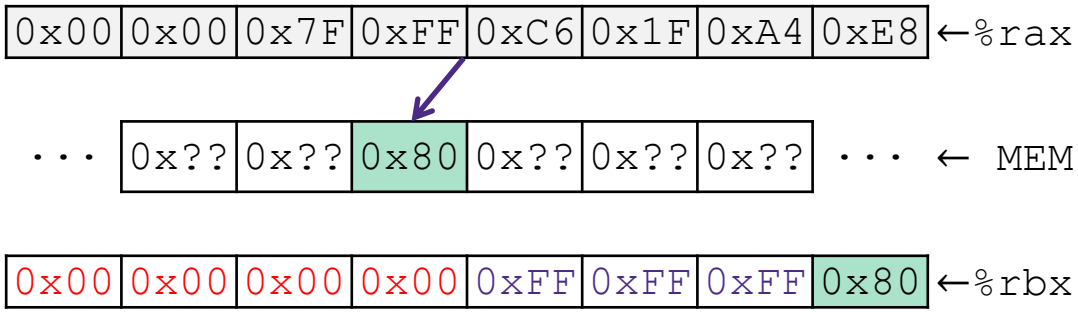
D – size of dest (**`w`** = 2 bytes, **`l`** = 4, **`q`** = 8)

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



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;
```

```
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;
}
```

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…

```
absdiff:

   ________________

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

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;
}
```

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

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;
}
```

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

- https://godbolt.org/g/Ovh3jN

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

BONUS SLIDES

Bonus content (nonessential). Does contain examples.

- Conditional Operator with Jumps
- Conditional Move

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

Conditional Move

Bonus Content (nonessential) *more details at end of slides*

- Conditional Move Instructions: **`cmov`*C*** `src, dst`
  - Move value from `src` to `dst` 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 <=,
  ret                #    result=else_val
```

Bonus Content (nonessential)

Using Conditional Moves

- Conditional Move Instructions
  - `cmov`*C* 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