CSE 351 Section 4

X86-64 Assembly

Administrivia

- Lab 2:

  → Due **next** Friday (2/4/2022)!

  → Make sure all your phase answers are followed by a newline character.

- Homework:

  → HW 9.2 Due **TOMORROW** (1/28/2022)!

  → HW 10.2 Due **Monday** (1/31/2022)!

x86-64 Assembly

x86-64 Assembly

Assembly language is a human-readable representation of machine code instructions (generally a one-to-one correspondence).

- Assembly is machine-specific
- Computer architecture and hardware are designed to execute a particular machine code instruction set

x86-64 Assembly

x86-64 is the primary 64-bit instruction set architecture (ISA) used by modern personal computers.

- It was developed by Intel and AMD and its 32-bit predecessor is called IA32.
- x86-64 is designed for complex instruction set computing (CISC), generally meaning it contains a larger set of more versatile and more complex instructions.

Other instruction sets include ARM (RISC) and PowerPC.

Data and Instructions

For this course, we will utilize only a small subset of x86-64's instruction set and omit floating point instructions. The subset of x86-64 instructions that we will use in this course take either one or two operands, usually in the form:

```
instruction operand1, operand2
```

There are three options for operands:

- Immediates: constants (e.g. `$0x400`)
- Registers: fast memory accessible to the CPU (e.g. `%rax`, `%edx`)
- Memory: memory addresses computed with `D(Rb, Ri, S)`
  - such as `0x400(%rdi, %rsi, 4)` = ***(%rdi + 4 * %rsi) + 0x400***

Address Computation

We can do more complicated memory accesses like so:

- `D(Rb, Ri, S)`
  - `Rb` - base register
  - `Ri` - index register
  - `S` - scale factor (1, 2, 4, 8)
  - `D` - displacement
  - Result is `D + Rb + Ri * S`

So `0x400(%rdi, %rsi, 4)` evaluates to `%rdi + 4 * %rsi + 0x400`. This is very useful for accessing elements in an array, and also for use in conjunction with `lea` (which does this address computation, but stores the raw result instead of accessing memory at the computed address).

Operand Size

The operation determines the effect of the operands on the processor state and has a suffix (“b” for byte, “w” for word, “l” for long, “q” for quad word) that determines the bit width of the operation. Sometimes the operation size can be inferred from the operands, so the suffix is omitted for brevity. For example:

- `movb src, dst` - copies 1 byte from src to dst
- `movw src, dst` - copies 2 bytes from src to dst
- `movl src, dst` - copies 4 bytes from src to dst
- `movq src, dst` - copies 8 bytes from src to dst

Midterm Reference Sheet

The reference sheet for the midterm is a great resource, especially for x86-64.

You can find it on the website here:
https://courses.cs.washington.edu/courses/cse351/21sp/exams/ref-mt.pdf

CSE 351 Reference Sheet (Midterm)

Binary	Decimal	Hex
0000	0	0
0001	1	1
0010	2	2
0011	3	3
0100	4	4
0101	5	5
0110	6	6
0111	7	7
1000	8	8
1001	9	9
1010	10	A
1011	11	B
1100	12	C
1101	13	D
1110	14	E
1111	15	F

2^0	2^1	2^2	2^3	2^4	2^5	2^6	2^7	2^8	2^9	2^{10}
1	2	4	8	16	32	64	128	256	512	1024

IEEE 754 FLOATING-POINT STANDARD

Value: $\pm 1 \times \text{Mantissa} \times 2^{\text{Exponent}}$

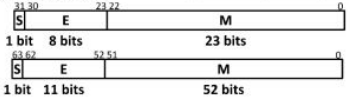
Bit fields: $(-1)^S \times 1.M \times 2^{(E-\text{bias})}$

where Single Precision Bias = 127,
Double Precision Bias = 1023.

IEEE 754 Symbols

E	M	Meaning
all zeros	all zeros	± 0
all zeros	non-zero	± denorm num
1 to MAX-1	anything	± norm num
all ones	all zeros	± ∞
all ones	non-zero	NaN

IEEE Single Precision and Double Precision Formats:



Assembly Instructions

`mov a, b`	Copy from `a` to `b`.
`movs a, b`	Copy from `a` to `b` with sign extension. Needs *two* width specifiers.
`movz a, b`	Copy from `a` to `b` with zero extension. Needs *two* width specifiers.
`lea a, b`	Compute address and store in `b`. *Note:* the scaling parameter of memory operands can only be 1, 2, 4, or 8.
`push src`	Push `src` onto the stack and decrement stack pointer.
`pop dst`	Pop from the stack into `dst` and increment stack pointer.
`call <func>`	Push return address onto stack and jump to a procedure.
`ret`	Pop return address and jump there.
`add a, b`	Add from `a` to `b` and store in `b` (and sets flags).
`sub a, b`	Subtract `a` from `b` (compute `b-a`) and store in `b` (and sets flags).
`imul a, b`	Multiply `a` and `b` and store in `b` (and sets flags).
`and a, b`	Bitwise AND of `a` and `b`, store in `b` (and sets flags).
`sar a, b`	Shift value of `b` *right* (*arithmetic*) by `a` bits, store in `b` (and sets flags).
`shr a, b`	Shift value of `b` *right* (*logical*) by `a` bits, store in `b` (and sets flags).
`shl a, b`	Shift value of `b` *left* by `a` bits, store in `b` (and sets flags).
`cmp a, b`	Compare `b` with `a` (compute `b-a` and set condition codes based on result).
`test a, b`	Bitwise AND of `a` and `b` and set condition codes based on result.
`jmp <label>`	Unconditional jump to address.
`j* <label>`	Conditional jump based on condition codes (*more on next page*).
`set* a`	Set byte `a` to 0 or 1 based on condition codes.

Conditionals

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

Registers

Name	Convention	Name of "virtual" register: Lowest 4 bytes	Lowest 2 bytes	Lowest byte
`%rax`	Return value – **Caller** saved	`%eax`	`%ax`	`%al`
`%rbx`	**Callee** saved	`%ebx`	`%bx`	`%bl`
`%rcx`	Argument #4 – **Caller** saved	`%ecx`	`%cx`	`%cl`
`%rdx`	Argument #3 – **Caller** saved	`%edx`	`%dx`	`%dl`
`%rsi`	Argument #2 – **Caller** saved	`%esi`	`%si`	`%sil`
`%rdi`	Argument #1 – **Caller** saved	`%edi`	`%di`	`%dil`
`%rsp`	Stack Pointer	`%esp`	`%sp`	`%spl`
`%rbp`	**Callee** saved	`%ebp`	`%bp`	`%bpl`
`%r8`	Argument #5 – **Caller** saved	`%r8d`	`%r8w`	`%r8b`
`%r9`	Argument #6 – **Caller** saved	`%r9d`	`%r9w`	`%r9b`
`%r10`	**Caller** saved	`%r10d`	`%r10w`	`%r10b`
`%r11`	**Caller** saved	`%r11d`	`%r11w`	`%r11b`
`%r12`	**Callee** saved	`%r12d`	`%r12w`	`%r12b`
`%r13`	**Callee** saved	`%r13d`	`%r13w`	`%r13b`
`%r14`	**Callee** saved	`%r14d`	`%r14w`	`%r14b`
`%r15`	**Callee** saved	`%r15d`	`%r15w`	`%r15b`

Sizes

C type	x86-64 suffix	Size (bytes)
`char`	`b`	1
`short`	`w`	2
`int`	`l`	4
`long`	`q`	8

Interpreting Instructions

What do the following assembly instructions do?

X86-64 instruction	English equivalent
movq $351, %rax	Move the number 351 into 8-byte (quad) register “rax”
addq %rdi, %rsi	Add the 64-bit value of %rdi to %rsi
movq (%rdi), %r8	Move the 64-bit data at the address stored in %rdi to %r8
leaq (%rax,%rax,8), %rax	Compute 9 * %rax, and store the 64-bit result in %rax

Procedure Basics

There are several instructions which manipulate the stack. Note that `%rsp` is the stack pointer, which holds the address of the last thing pushed to the stack.

- `push x`
  - Decrements stack pointer (stack grows down!) and places value x at %rsp
- `pop x`
  - Copies value at %rsp to x and increments stack pointer.
- `call x`
  - Pushes address of following instruction (“return address”) to stack and jumps to x.
- `ret`
  - Pops to %rip (gets return address from stack and sets instruction pointer)

Passing Arguments

By convention, **`%rax`** is used for the return value.

The first six arguments to procedure calls are passed in the order:

`%rdi`, **`%rsi`**, **`%rdx`**, **`%rcx`**, **`%r8`**, **`%r9`**

(Diane's silk dress cost $89)

- What if we have more than 6 arguments?
- What if need to preserve a register's value before and after a function call?

Exercise!

Exercise 1

Symbolically, what does the following code return? Remember, register %rax is used to store the return value.

```
movl (%rdi), %eax              # %rdi -> x    *x
leal (%eax,%eax,2), %eax       # %rax -> r    *x * 3
addl %eax, %eax                             (*x * 3) * 2
andl %esi, %eax                # %esi -> y    (*x * 6) & y
subl %esi, %eax                             ((*x * 6) & y) - y
ret
```

Conditionals

Condition Codes

Condition codes include the zero, sign, carry (unsigned overflow), and (signed) overflow flags. They are stored on the processor in their own register.

- They are implicitly set by arithmetic operations:
  - `addq src, dst`
    - `r = dst + src` (result used to set flags)
- There are also instructions to set only the condition codes:
  - `cmp a, b`
    - `r = b - a` (result sets flags, but is not stored)
  - `test a, b`
    - `r = a & b` (result sets flags, but is not stored)

Control Flow

The condition codes are often used in combination with j* (jump) and set* instructions. These instructions take one operand and change the instruction pointer or given byte respectively depending on different combinations of the condition codes.

Conditionals

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

Exercise 3

Write an equivalent C function for the following x86-64 code:

```
mystery:
  testl   %edx, %edx
  js      .L3
  cmpl    %esi, %edx
  jge     .L3
  movslq  %edx, %rdx
  movl    (%rdi,%rdx,4), %eax
  ret
.L3:
  movl    $0, %eax
  ret
```

Exercise 3

```
mystery:
  testl   %edx, %edx
  js      .L3
  cmpl    %esi, %edx
  jge     .L3
  movslq  %edx, %rdx
  movl    (%rdi,%rdx,4), %eax
  ret
.L3:
  movl    $0, %eax
  ret
```

Exercise 3

```
mystery:
  testl   %edx, %edx
  js      .L3
  cmpl    %esi, %edx
  jge     .L3
  movslq  %edx, %rdx
  movl    (%rdi,%rdx,4), %eax
  ret
.L3:
  movl    $0, %eax
  ret
```

```
int mystery(? x, int y, int z)
```

Exercise 3

```
mystery:
  testl   %edx, %edx
  js      .L3
  cmpl    %esi, %edx
  jge     .L3
  movslq  %edx, %rdx
  movl    (%rdi,%rdx,4), %eax
  ret
.L3:
  movl    $0, %eax
  ret
```

```
int mystery(? x, int y, int z) {
  if ( )

  else

}
```

Exercise 3

```
mystery:
  testl   %edx, %edx
  js      .L3
  cmpl    %esi, %edx
  jge     .L3
  movslq  %edx, %rdx
  movl    (%rdi,%rdx,4), %eax
  ret
.L3:
  movl    $0, %eax
  ret
```

```
int mystery(? x, int y, int z) {
  if (z >= 0 && z < y)

  else

}
```

Conditionals

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

Exercise 3

```
mystery:
  testl   %edx, %edx
  js      .L3
  cmpl    %esi, %edx
  jge     .L3
  movslq  %edx, %rdx
  movl    (%rdi,%rdx,4), %eax
  ret
.L3:
  movl    $0, %eax
  ret
```

```
int mystery(int *x, int y, int z) {
  if (z >= 0 && z < y)
    return x[z];

  else

}
```

Exercise 3

```
mystery:
  testl   %edx, %edx
  js      .L3
  cmpl    %esi, %edx
  jge     .L3
  movslq  %edx, %rdx
  movl    (%rdi,%rdx,4), %eax
  ret
.L3:
  movl    $0, %eax
  ret
```

```
int mystery(int *x, int y, int z) {
  if (z >= 0 && z < y)
    return x[z];

  else
    return 0;
}
```

Exercise 2

Convert the following C function into x86-64 assembly code. You are not being judged on the efficiency of your code – just correctness.

```
long happy(long *x, long y, long z) {
    if (y > z)
        return z + y;
    else
        return *x;
}
```

Exercise 2

Convert the following C function into x86-64 assembly code. You are not being judged on the efficiency of your code – just correctness.

```
happy:
    cmpq %rdx, %rsi
    jle .else
    leaq (%rdx, %rsi), %rax
    ret
.else:
    movq (%rdi), %rax
    ret
```

Multiple other possibilities (e.g. switch ordering of if/else clauses, replace lea with mov/add instruction pair).

GDB

The GNU Debugger (GDB)

The GNU Debugger (GDB) is a powerful debugging tool that will be critical to Lab 2 and Lab 3 and is a useful tool to know as a programmer moving forward.

There are tutorials and reference sheets available on the course webpage.

Make sure that you're familiar with GDB because you'll be using it a lot on labs 2 and 3.

Take some time to learn helpful commands like `bt (backtrace)` and `tui/layout`.

That's All, Folks!

Thanks for attending section! Feel free to stick around for a bit if you have quick questions (otherwise post on Ed or go to office hours).

See you all next week! :-)