x86-64 Programming II

CSE 351 Autumn 2022

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http://xkcd.com/99/

Relevant Course Information

- Lab submissions that fail the autograder get a **ZERO**
  - No excuses – make full use of tools & Gradescope's interface
  - Leeway on Lab 1a won't be given moving forward
- Lab 2 (x86-64) released today
  - Learn to trace x86-64 assembly and use GDB
- Midterm is in two weeks (take home, 11/3–5)
  - Open book; make notes and use midterm reference sheet
  - Individual, but discussion allowed via "Gilligan's Island Rule"
  - Mix of "traditional" and design/reflection questions
    - Form study groups and look at past exams!

Extra Credit

- All labs starting with Lab 2 have extra credit portions
  - These are meant to be fun extensions to the labs

- Extra credit points *don't* affect your lab grades
  - From the course policies: “they will be accumulated over the course and will be used to bump up borderline grades at the end of the quarter.”
  - Make sure you finish the rest of the lab before attempting any extra credit

Reading Review

- Terminology:
  - Address Computation Instruction (`lea`)
  - Condition codes: Carry Flag (`CF`), Zero Flag (`ZF`), Sign Flag (`SF`), and Overflow Flag (`OF`)
  - Test (`test`) and compare (`cmp`) assembly instructions
  - Jump (`j*`) and set (`set*`) families of assembly instructions

- Questions from the Reading?

Memory Addressing Modes (Review)

ar[i] ⟷ *(ar + i) → Mem[ar + i * sizeof(data type)]

- **General:**
  - D(Rb,Ri,S)   Mem[Reg[Rb]+Reg[Ri]*S+D]
    - Rb: Base register (any register)
    - Ri: Index register (any register except %rsp)
    - S: Scale factor (1, 2, 4, 8) *– why these numbers?*   data type widths
    - D: Constant displacement value (a.k.a. immediate)

- **Special cases** (see CSPP Figure 3.3 on p.181)

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

so reg name not interpreted as Rb

Address Computation Instruction (Review)

"Mem" Reg

- `leaq src, dst`
  - "`lea`" stands for *load effective address*
  - `src` is address expression (any of the formats we've seen)
    ↳ calculates Reg[Rb]+Reg[Ri]*S+D ~~Mem[ ]~~
  - `dst` is a register
  - Sets `dst` to the *address* computed by the `src` expression (does not go to memory! – it just does math)
  - Example: `leaq (%rdx,%rcx,4), %rax`
- Uses:
  - Computing addresses without a memory reference
    - *e.g.*, translation of `p = &x[i];` address-of operator
  - Computing arithmetic expressions of the form `x+k*i+d`
    Reg[Rb]+Reg[Ri]*S+D
    - Though k can only be 1, 2, 4, or 8

Review Questions

- If `%rdx = 0xf000` and `%rcx = 0x100`, what addresses are dereferenced by the following memory operands?
  - `(%rdx, %rcx)` — Rb: `%rdx`, Ri: `%rcx`

    Reg[Rb]+Reg[Ri]*1

    $\boxed{0xf100}$
  - `0x80(,%rdx,2)` — D: `0x80`, Ri: `%rdx`, S: `2`

    Reg[Ri]*2+0x80

    $\boxed{0x1e080}$

    0xf000*2 = 0xf000 << 1 = 0x1e000

- Which of the following x86-64 instructions correctly calculates `%rax=9*%rdi`?

  no memory access, so must be lea

  S ∈ {1,2,4,8}

  - A. `leaq (,%rdi,~~9~~), %rax` — invalid syntax
  - B. `~~movq~~ (,%rdi,9), %rax` — invalid syntax
  - [✓ C.] `leaq (%rdi,%rdi,8), %rax` — %rax = 9*%rdi
  - D. `~~movq~~ (%rdi,%rdi,8), %rax` — %rax = Mem[9*%rdi]

Example: Basic Arithmetic

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

arbitrary! (for now...)

don't actually need new variables!

```
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;
```

must return in %rax

instr src , dst

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

Example: Using Memory

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

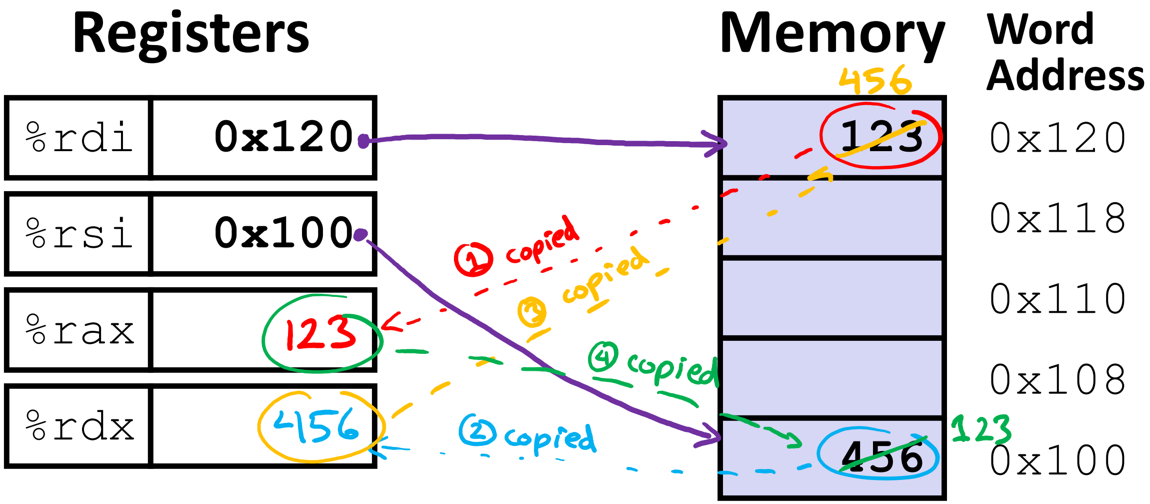
Compiler Explorer:
https://godbolt.org/z/c9M9fMefa

memory operands register operands

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

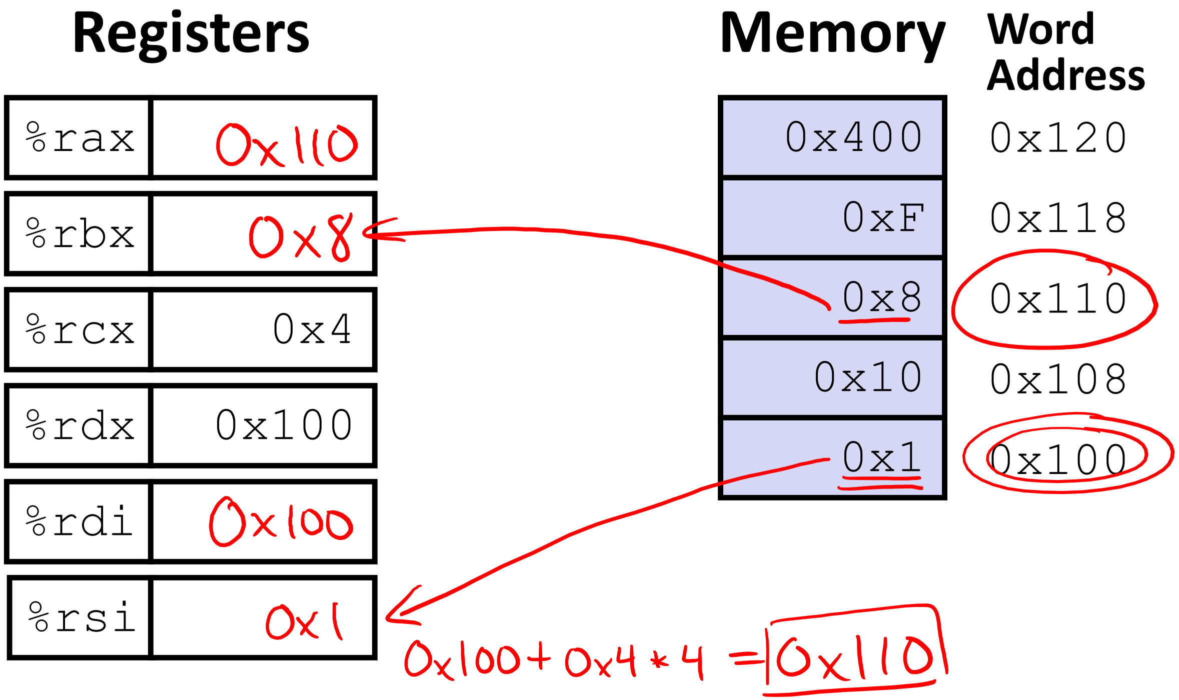
Register		Variable
%rdi	⇔	xp
%rsi	⇔	yp
%rax	⇔	t0
%rdx	⇔	t1

Example: Using Memory



```
swap:
①  movq   (%rdi), %rax    #  t0 = *xp
②  movq   (%rsi), %rdx    #  t1 = *yp
③  movq   %rdx, (%rdi)    # *xp =  t1
④  movq   %rax, (%rsi)    # *yp =  t0
    ret
```

Example: lea vs. mov



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

$0x100 + 0x4 * 4 = \boxed{0x110}$

Rb Ri S

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

0x100

→ 0x110 ("addr")

→ 0x8 (data)

→ 0x100 ("addr")

→ 0x1 (data)

Example: lea Arithmetic

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;      ← replaced by lea & shift
  long t5 = t3 + t4;
  long rval = t2 * t5;
  return rval;
}
```

```
arith:
            x     y
  leaq     (%rdi,%rsi), %rax      # rax = x+y (t1)
            z
  addq     %rdx, %rax             # rax = x+y+z (t2)
            y     y
  leaq     (%rsi,%rsi,2), %rdx    # rdx = 3y
  salq     $4, %rdx               # rdx = 48y (t4)
  leaq     4(%rdi,%rdx), %rcx
  imulq    %rcx, %rax    ← multiplying two variables
  ret
```

- Interesting Instructions
  - leaq: “address” computation
  - salq: shift
  - imulq: multiplication
    - Only used once!

Example: lea Arithmetic

```
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

limited registers means they often get reused!

```
arith:                                       comment (AT&T syntax)
  leaq    (%rdi,%rsi), %rax       # rax/t1   = x + y
  addq    %rdx, %rax   S∈{1,2,4,8} # 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
```

Control Flow

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

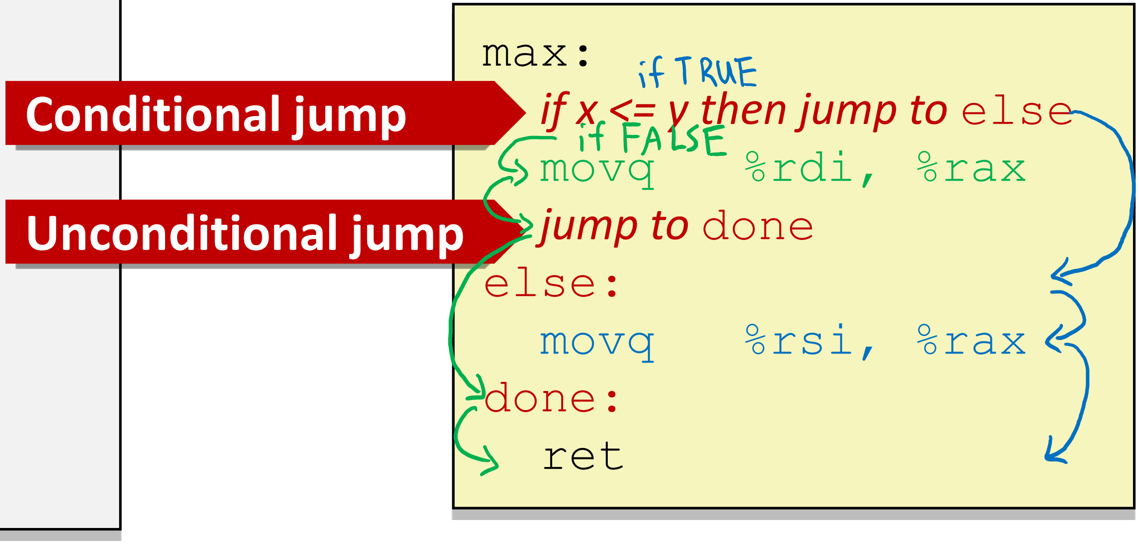
```
long max(long x, long y)
{
   long max;
   if (x > y) {
      max = x;
   } else {
      max = y;
   }
   return max;
}
```

```
max:
   ???
   movq    %rdi, %rax   # if case
   ???
   ???
   movq    %rsi, %rax   # else case
   ???
   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`** `{…}`

Summary

- **Memory Addressing Modes:** The addresses used for accessing memory in `mov` (and other) instructions can be computed in several different ways
  - *Base register*, *index register*, *scale factor*, and *displacement* map well to pointer arithmetic operations
- **Load effective address** (`lea`) instruction used to compute addresses and perform basic arithmetic
  - *Doesn't* dereference the source memory operand, unlike all other instructions!
- Control flow in x86 determined by Condition Codes