Lecture 04
Machine-Level Programming – part 2

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Slides adapted from Randy Bryant and Dave O'Hallaron: Introduction to Computer Systems, CMU

Example of Basic Addressing Modes

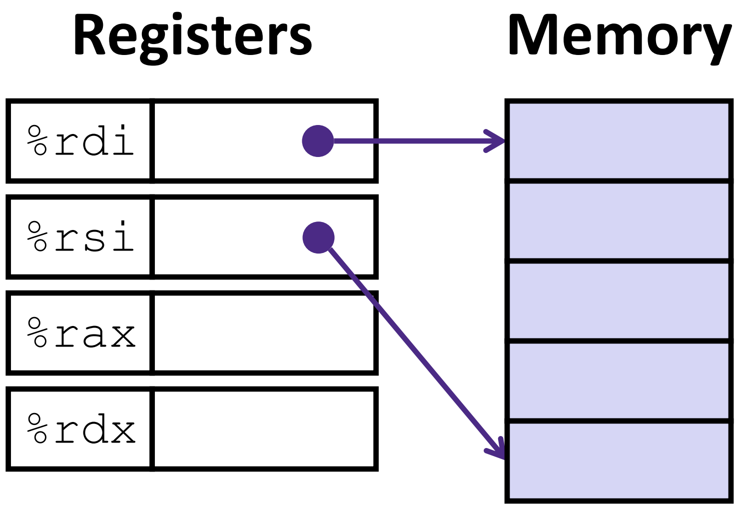
```c
void swap(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

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

Compiler Explorer:
https://godbolt.org/z/zc4Pcq

Understanding `swap()`

```
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
```

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

Understanding swap()

Registers

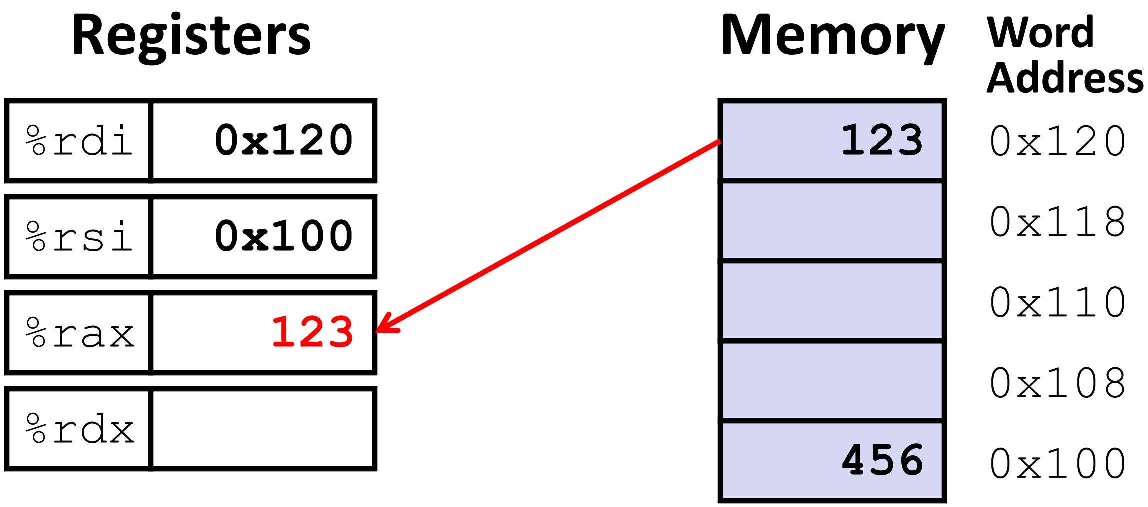
%rdi	**0x120**
%rsi	**0x100**
%rax	
%rdx	

Memory

Memory	Word Address
123	0x120
	0x118
	0x110
	0x108
456	0x100

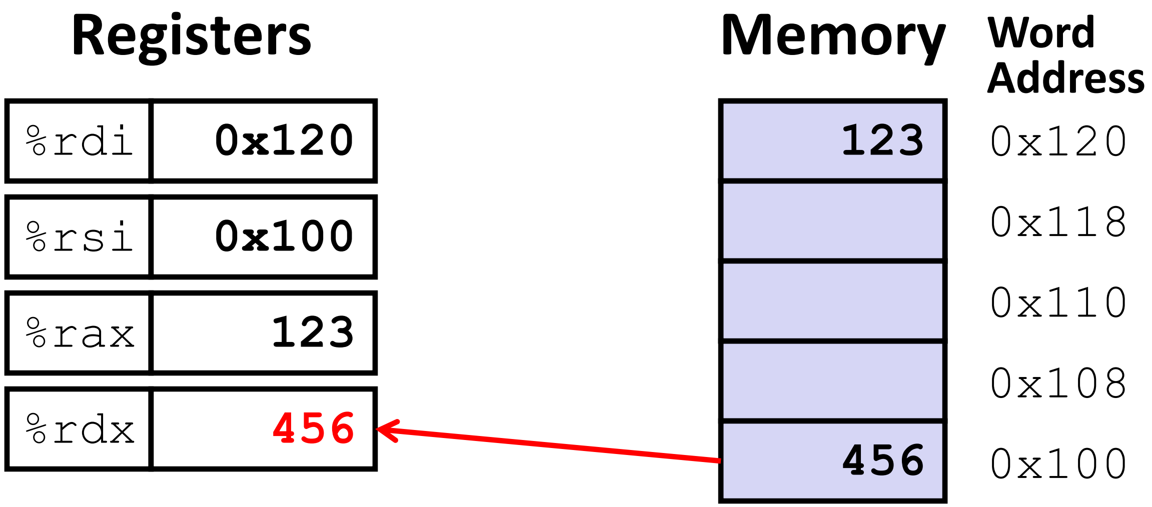
```
swap:
   movq   (%rdi), %rax   #  t0 = *xp
   movq   (%rsi), %rdx   #  t1 = *yp
   movq   %rdx, (%rdi)   # *xp =  t1
   movq   %rax, (%rsi)   # *yp =  t0
   ret
```

Understanding swap()



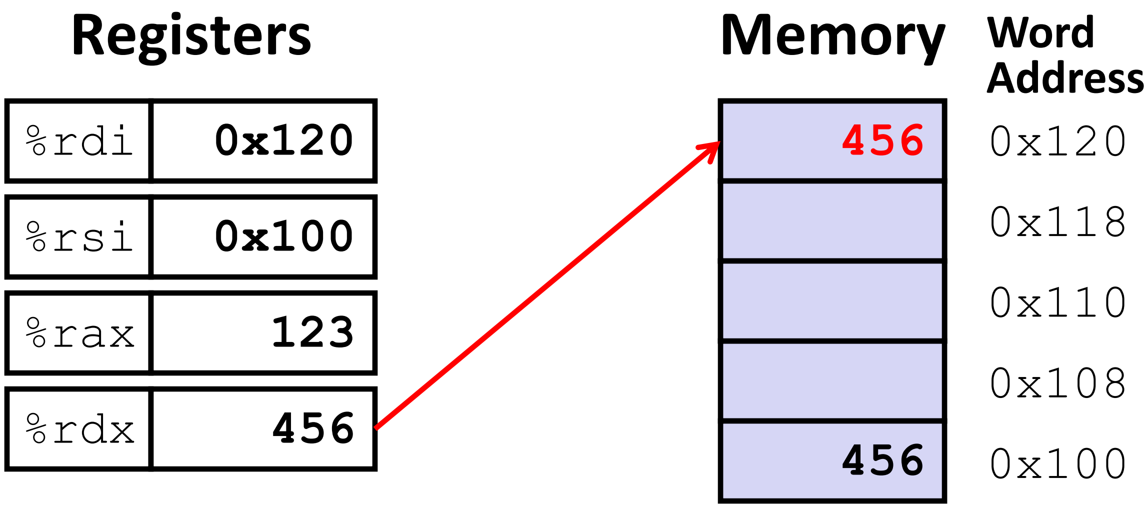

```
swap:
   movq   (%rdi), %rax   #  t0 = *xp
   movq   (%rsi), %rdx   #  t1 = *yp
   movq   %rdx, (%rdi)   # *xp =  t1
   movq   %rax, (%rsi)   # *yp =  t0
   ret
```

Understanding `swap()`



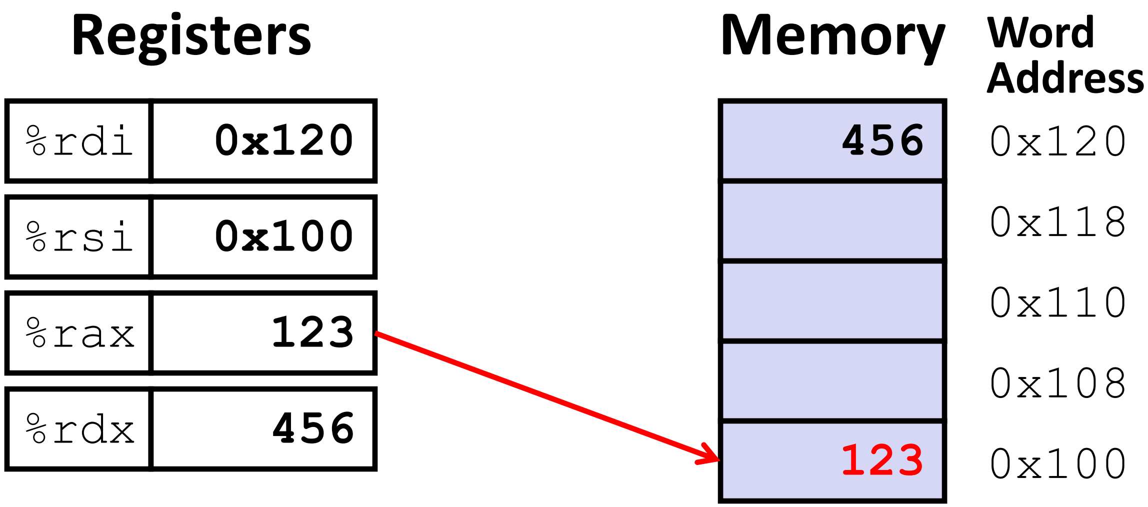

```
swap:
    movq   (%rdi), %rax   #  t0 = *xp
    movq   (%rsi), %rdx   #  t1 = *yp
    movq   %rdx, (%rdi)   # *xp =  t1
    movq   %rax, (%rsi)   # *yp =  t0
    ret
```

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[Reg[R]]
  - Data in register `R` specifies the memory address
  - Like pointer dereference in C
  - <u>Example</u>: **`movq`** `(%rcx), %rax`

- **Displacement:** `D(R)` Mem[Reg[R]+D]
  - Data in register `R` specifies the *start* of some memory region
  - Constant displacement `D` specifies the offset from that address
  - <u>Example</u>: **`movq`** `8(%rbp), %rdx`

Complete Memory Addressing Modes

- **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?*
    - `D`: Constant displacement value (a.k.a. immediate)

- **Special cases** (see CS:APP3e 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)`

Address Computation Examples

%rdx	0xf000
%rcx	0x0100

D(Rb,Ri,S) →
Mem[Reg[Rb]+Reg[Ri]*S+D]

Expression	Address Computation	Address
0x8(%rdx)		
(%rdx,%rcx)		
(%rdx,%rcx,4)		
0x80(,%rdx,2)		

Address Computation Instruction

- `leaq src, dst`
  - `"lea"` stands for *load effective address*
  - `src` is address expression (any of the formats we've seen)
  - `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];`
  - Computing arithmetic expressions of the form `x+k*i+d`
    - Though `k` can only be 1, 2, 4, or 8

Example: `lea` vs. `mov`

Registers

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

Memory	Word 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
```

`lea`

`lea` – "It just does math"

Arithmetic Example

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;
  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
```

- Interesting Instructions
  - `leaq`: "address" computation
  - `salq`: shift
  - `imulq`: multiplication
    - Only used once!

Arithmetic Example

Register	Use(s)
%rdi	x
%rsi	y
%rdx	z, t4
%rax	t1, t2, rval
%rcx	t5

```
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     # rax/t1   = x + y
  addq    %rdx, %rax            # 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
   ???
   ???
   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`** {…}

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
- Control flow in x86 determined by Condition Codes