x86-64 Programming I

CSE 351 Spring 2019

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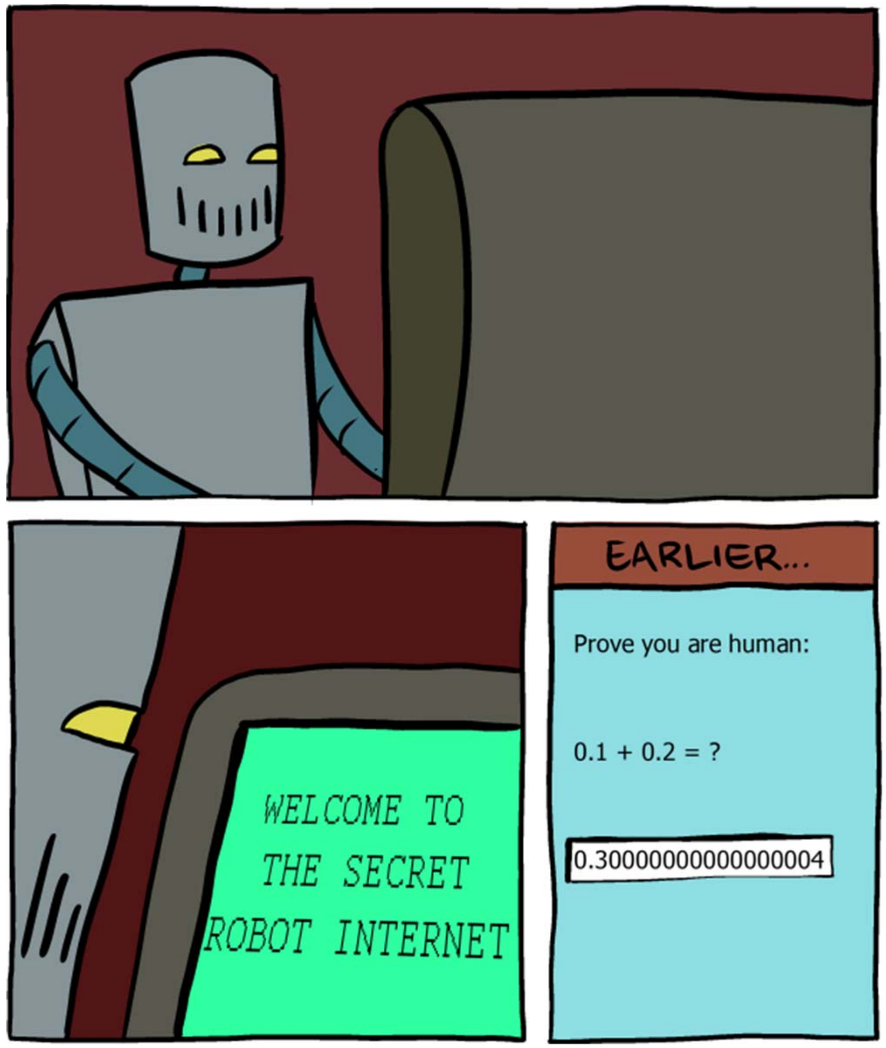

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Administrivia

- Lab 1b due Monday (4/22)
  - Submit `bits.c` and `lab1Breflect.txt`
- Homework 2 due Wednesday (4/24)
  - On Integers, Floating Point, and x86-64
- Lab 2 (x86-64) coming soon, due Wednesday (5/01)

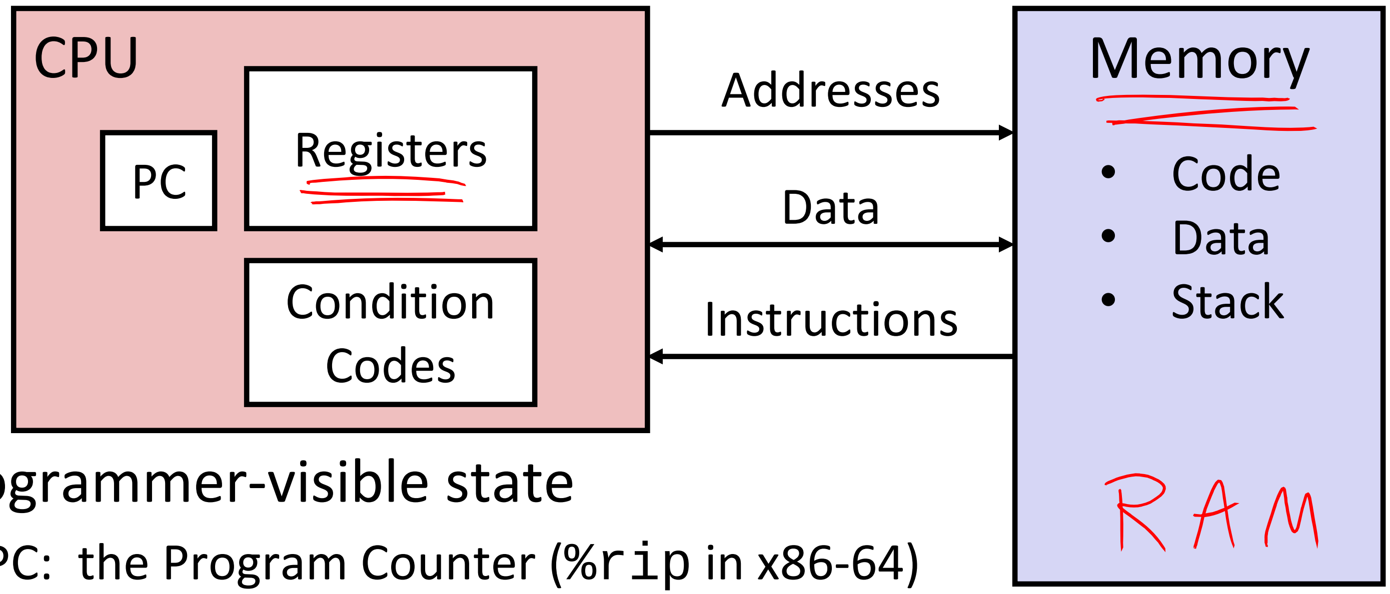
Non-Compiling Code

- You get a zero on the assignment
  - No excuses – you have access to our grading environment

Writing Assembly Code? In 2019???

- Chances are, you'll never write a program in assembly, but understanding assembly is the key to the machine-level execution model:
  - Behavior of programs in the presence of bugs
    - When high-level language model breaks down
  - Tuning program performance
    - Understand optimizations done/not done by the compiler
    - Understanding sources of program inefficiency
  - Implementing systems software
    - What are the "states" of processes that the OS must manage
    - Using special units (timers, I/O co-processors, etc.) inside processor!
  - Fighting malicious software
    - Distributed software is in binary form

Assembly Programmer's View



- Programmer-visible state
  - PC: the Program Counter (`%rip` in x86-64)
    - Address of next instruction
  - Named registers
    - Together in "register file"
    - Heavily used program data
  - Condition codes
    - Store status information about most recent arithmetic operation
    - Used for conditional branching

- Memory
  - Byte-addressable array
  - Code and user data
  - Includes *the Stack* (for supporting procedures)

x86-64 Assembly "Data Types"

- Integral data of 1, 2, 4, or 8 bytes
  - Data values
  - Addresses
- Floating point data of 4, 8, 10 or 2x8 or 4x4 or 8x2
  - Different registers for those (*e.g.* %xmm1, %ymm2)
  - Come from *extensions to x86* (SSE, AVX, …)

Not covered In 351

- No aggregate types such as arrays or structures
  - Just contiguously allocated bytes in memory
- Two common syntaxes
  - ✓ "AT&T": used by our course, slides, textbook, gnu tools, …
  - X "Intel": used by Intel documentation, Intel tools, …
  - Must know which you're reading

operation op1, op2

What is a Register?

- A location in the CPU that stores a small amount of data, which can be accessed very quickly (once every clock cycle)

- Registers have *names*, not *addresses*
  - In assembly, they start with % (*e.g.* `%rsi`)

- Registers are at the heart of assembly programming
  - They are a precious commodity in all architectures, but *especially* x86 only 16 of them...

word

x86-64 Integer Registers – 64 bits wide

"64-bit names"

%rax	%eax	%r8	%r8d
%rbx	%ebx	%r9	%r9d
%rcx	%ecx	%r10	%r10d
%rdx	%edx	%r11	%r11d
%rsi	%esi	%r12	%r12d
%rdi	%edi	%r13	%r13d
%rsp	%esp	%r14	%r14d
%rbp	%ebp	%r15	%r15d

"32-bit names"

- Can reference low-order 4 bytes (also low-order 2 & 1 bytes)

Some History: IA32 Registers – 32 bits wide

32 bits (same as last slide)

h = higher   l = lower   8 bits

16 bits

	32-bit	16-bit virtual registers (backwards compatibility)			Name Origin (mostly obsolete)
general purpose	%eax	%ax	%ah	%al	accumulate
general purpose	%ecx	%cx	%ch	%cl	counter
general purpose	%edx	%dx	%dh	%dl	data
general purpose	%ebx	%bx	%bh	%bl	base
general purpose	%esi	%si			source index
general purpose	%edi	%di			destination index
	%esp	%sp			stack pointer
	%ebp	%bp			base pointer

16-bit virtual registers (backwards compatibility)

Name Origin (mostly obsolete)

Memory vs. Registers

❖ Addresses	**vs.**	Names
▪ `0x7FFFD024C3DC`		`%rdi`
❖ Big	**vs.**	Small
▪ ~ 8 GiB		(16 x 8 B) = 128 B 64bits
❖ Slow	**vs.**	Fast
▪ ~50-100 ns		sub-nanosecond timescale
❖ Dynamic	**vs.**	Static
▪ Can "grow" as needed while program runs		fixed number in hardware

Three Basic Kinds of Instructions

1) Transfer data between memory and register
   - *Load* data from memory into register
     - `%reg` = Mem[address]
   - *Store* register data into memory
     - Mem[address] = `%reg`

Remember: Memory is indexed just like an array of bytes!

2) Perform arithmetic operation on register or memory data
   - `c = a + b;     z = x << y;     i = h & g;`

3) Control flow: what instruction to execute next
   - Unconditional jumps to/from procedures
   - Conditional branches

Operand types

operation op1, op2

- ***Immediate:*** Constant integer data
  - Examples: **`$0x400`**, **`$-533`**
    hex decimal
  - Like C literal, but prefixed with **`'$'`**
  - Encoded with 1, 2, 4, or 8 bytes *depending on the instruction*
- ***Register:*** 1 of 16 integer registers
  - Examples: **`%rax`**, **`%r13`**
  - But **`%rsp`** reserved for special use
  - Others have special uses for particular instructions
- ***Memory:*** Consecutive bytes of memory at a computed address
  - Simplest example: **`(%rax)`** = Memory [%rax]
    take data in %rax, treat as address, pull data at that address
  - Various other "address modes"

%rax
%rcx
%rdx
%rbx
%rsi
%rdi
%rsp (stack pointer)
%rbp
%r~~#~~ r8 - r15

16 regs total

x86-64 Introduction

- Data transfer instruction (`mov`)
- Arithmetic operations
- Memory addressing modes
  - `swap` example
- Address computation instruction (`lea`)

Moving Data

width specifier

instruction name

copies data

- General form: `mov_ source, destination`
  - Missing letter (_) specifies size of operands
  - Note that due to backwards-compatible support for 8086 programs (16-bit machines!), "word" means 16 bits = 2 bytes in x86 instruction names
  - Lots of these in typical code

- `movb src, dst`
  - Move 1-byte "**b**yte"
- `movw src, dst`
  - Move 2-byte "**w**ord"
- `movl src, dst`
  - Move 4-byte "**l**ong word"
- `movq src, dst`
  - Move 8-byte "**q**uad word"

movq Operand Combinations

movq src, dst

x86 | C
Imm ⟷ Constant
Reg ⟷ Variable
Mem ⟷ dereferencing a pointer

	Source	Dest	Src, Dest	C Analog
movq	Imm	Reg	`movq $0x4, %rax`	`var_a = 0x4;`
		Mem	`movq $-147, (%rax)`	`*p_a = -147;`
	Reg	Reg	`movq %rax, %rdx`	`var_d = var_a;`
		Mem	`movq %rax, (%rdx)`	`*p_d = var_a;`
	Mem	Reg	`movq (%rax), %rdx`	`var_d = *p_a;`

- *Cannot do memory-memory transfer with a single instruction*
  - How would you do it?

① Mem → Reg movq (%rax), %rdx
② Reg → Mem movq %rdx, (%rbx)

Some Arithmetic Operations

other ways to set to 0:
subq %rcx, %rcx
andq $0, %rcx
xorq %rcx, %rcx
imulq $0, %rcx

- Binary (two-operand) Instructions:
  - **Maximum of one memory operand**
  - Beware argument order!
  - No distinction between signed and unsigned
    - Only arithmetic vs. logical shifts
  - How do you implement "r3 = r1 + r2"?

Imm, Reg, or Mem

Format	Computation	
`addq src, dst`	*dst = dst + src*	(*dst += src*)
`subq src, dst`	*dst = dst – src*	
`imulq src, dst`	*dst = dst * src*	signed mult
`sarq src, dst`	*dst = dst >> src*	**A**rithmetic
`shrq src, dst`	*dst = dst >> src*	**L**ogical
`shlq src, dst`	*dst = dst << src*	(same as `salq`)
`xorq src, dst`	*dst = dst ^ src*	
`andq src, dst`	*dst = dst & src*	
`orq src, dst`	*dst = dst | src*	

operation

operand size specifier (b, w, l, q)

"r3 = r1 + r2"?
%rcx %rax %rbx

① clear r3
② add r1 to r3
③ add r2 to r3
⇒
movq $0, %rcx
addq %rax, %rcx
addq %rbx, %rcx

movq %rax, %rcx
addq %rbx, %rcx

Some Arithmetic Operations

- Unary (one-operand) Instructions:

Format	Computation	
`incq` *dst*	*dst = dst + 1*	increment
`decq` *dst*	*dst = dst – 1*	decrement
`negq` *dst*	*dst = –dst*	negate
`notq` *dst*	*dst = ~dst*	bitwise complement

- See CSPP Section 3.5.5 for more instructions: `mulq`, `cqto`, `idivq`, `divq`

Arithmetic Example

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

convention!

```
long simple_arith(long x, long y)
{                        don't actually need new variables!
  long t1 = x + y;
  long t2 = t1 * 3;
  return t2;
}
```

```
y += x;
y *= 3;
long r = y;   } must return
return r;     } in %rax
```

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

Example of Basic Addressing Modes

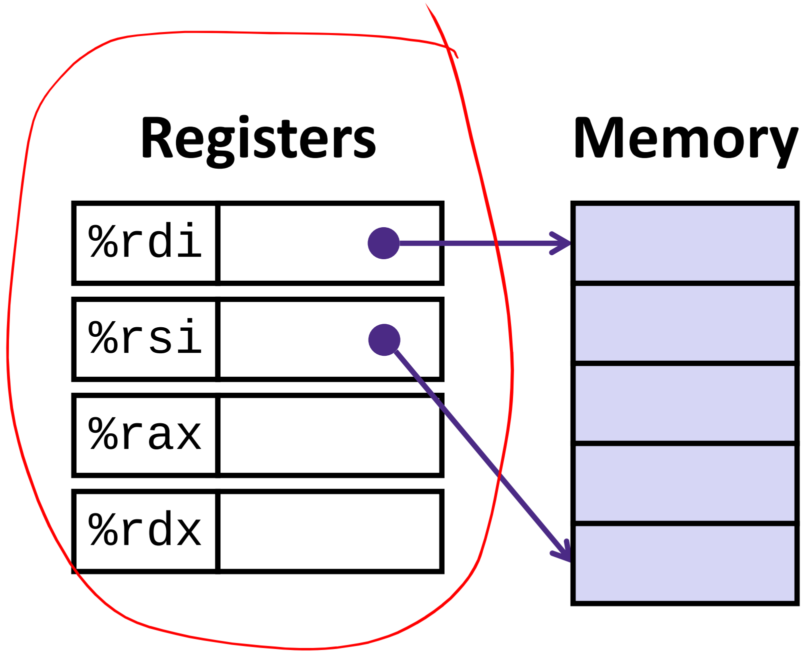
```
void swap(long *xp, long *yp)
{
  long t0 = *xp;
  long t1 = *yp;
  *xp = t1;
  *yp = t0;
}
```

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

Mem operands

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

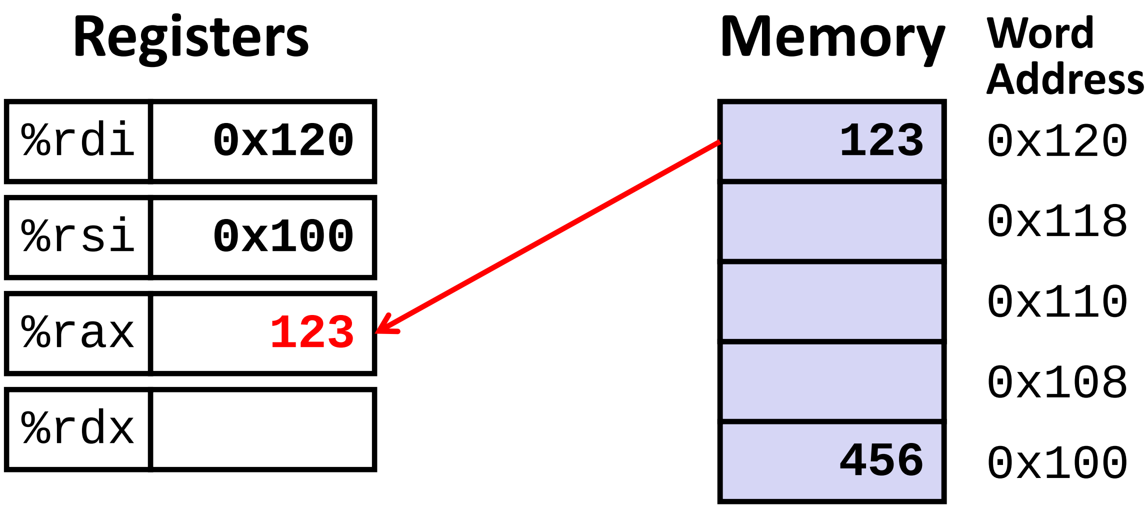
Memory	Word Address
123	0x120
	0x118
	0x110
	0x108
456	0x100

src dst

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

comment

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()

Registers

%rdi	0x120
%rsi	0x100
%rax	123
%rdx	456

Memory

Memory	Word Address
123	0x120
	0x118
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```
swap:
   movq   (%rdi), %rax   #  t0 = *xp
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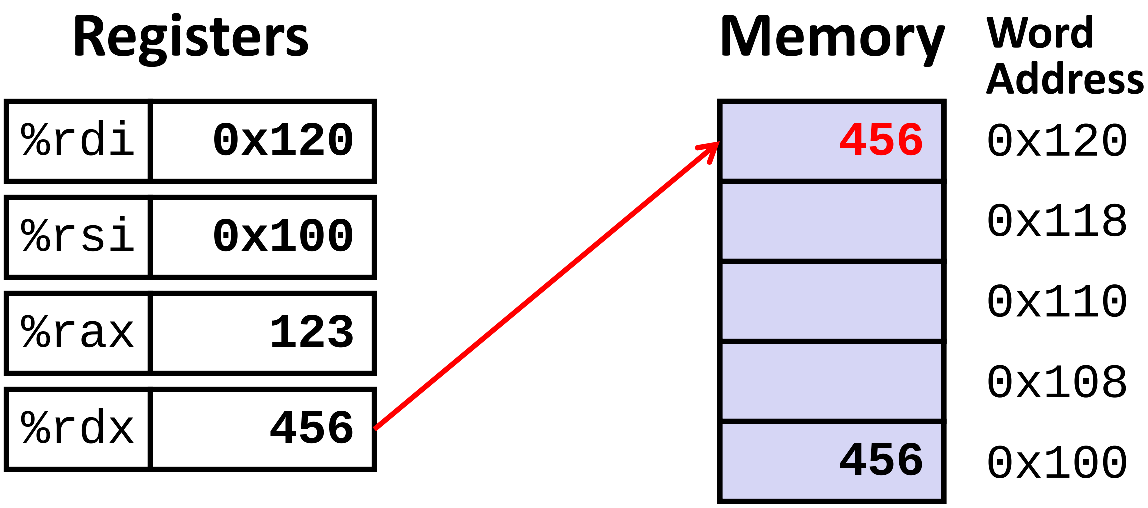
Understanding `swap()`

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   movq   (%rdi), %rax   #  t0 = *xp
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   ret
```
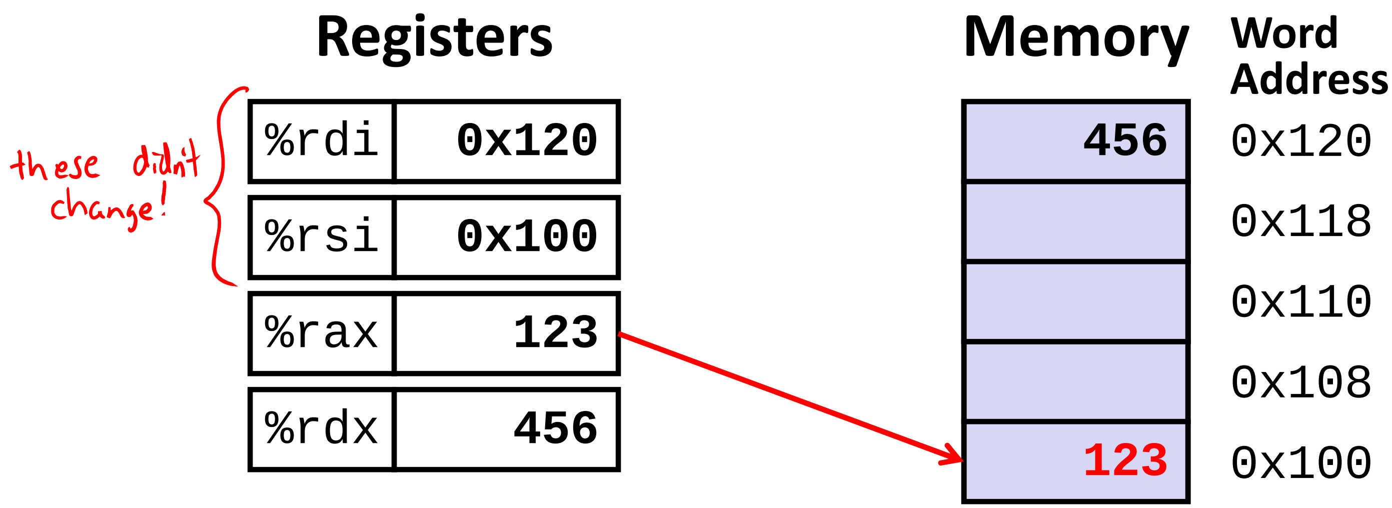

Understanding `swap()`




```
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

name of register
treat Mem as an array

- **Indirect:** (R) Mem[Reg[R]]

  value stored in register

  - Data in register R specifies the memory address
  - Like pointer dereference in C
  - Example: `movq (%rcx), %rax`

no space

- **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
  - Example: `movq 8(%rbp), %rdx`

rbp + 8

Complete Memory Addressing Modes

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) Default
  - `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

(if not specified) default values:

S = 1
D = 0
Reg[Rb] = 0
Reg[Ri] = 0

Address Computation Examples

%rdx	**0xf000**
%rcx	**0x0100**

D(Rb,Ri,S) →
Mem[Reg[Rb]+Reg[Ri]*S+D]

ignore the memory access for now

Expression	Address Computation	Address (8 bytes wide)
D Rb 0x8(%rdx)	Reg[Rb]+D = 0xf000 + 0x8	0xf008
Rb Ri (%rdx,%rcx)	Reg[Rb]+Reg[Ri]*1	0xf100
Rb Ri S (%rdx,%rcx,4)	*4	0xf400
D Ri S 0x80(,%rdx,2)	Reg[Ri]*2+0x80	0x1e080

0xf000*2
0xf000 << 1 = 0x1e000
1111 0000
1 1110 0000 ... 0

Summary

- There are 3 types of operands in x86-64
  - Immediate, Register, Memory
- There are 3 types of instructions in x86-64
  - Data transfer, Arithmetic, Control Flow

- **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