x86 Programming I

CSE 351 Autumn 2016

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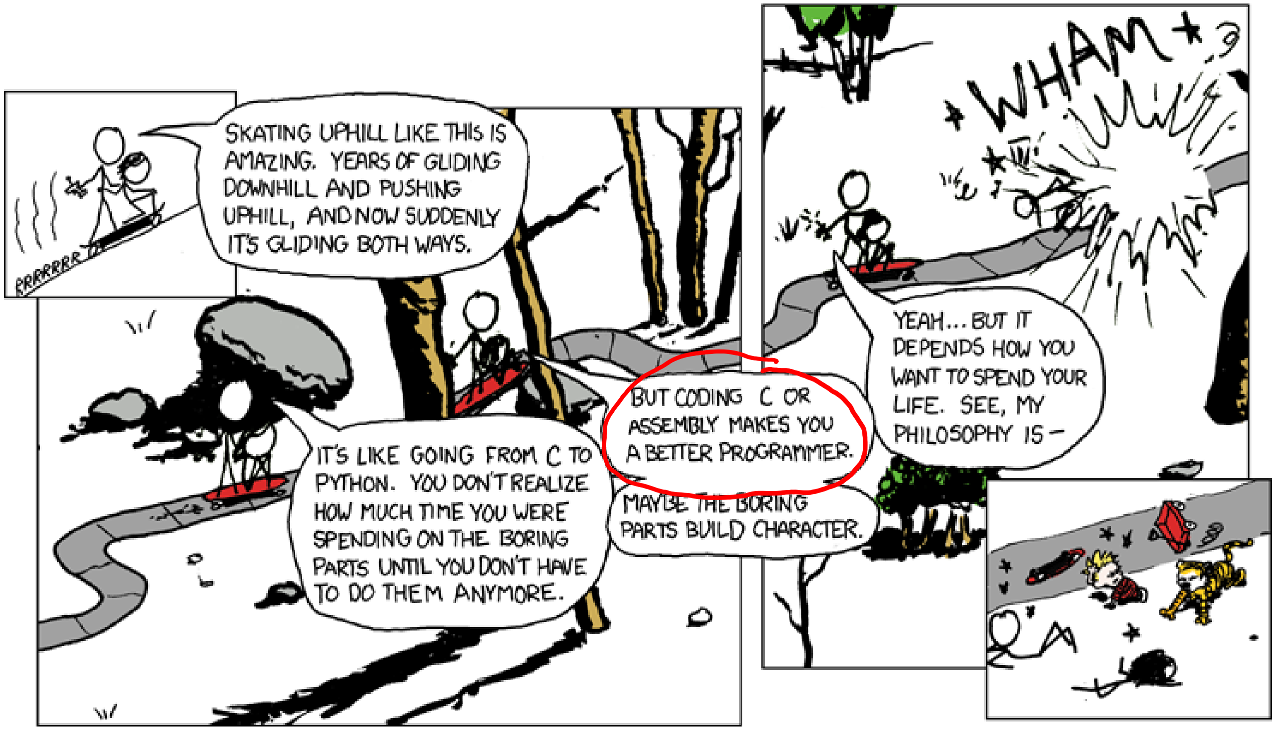


http://xkcd.com/409/

Administrivia

- Lab 1 due today at 5pm
  - You have *late days* available
- Lab 2 (x86 assembly) released next Tuesday (10/18)
- Homework 1 due next Friday (10/21)

Roadmap

C:

```
car *c = malloc(sizeof(car));
c->miles = 100;
c->gals = 17;
float mpg = get_mpg(c);
free(c);
```

Java:

```
Car c = new Car();
c.setMiles(100);
c.setGals(17);
float mpg =
    c.getMPG();
```

Assembly language:

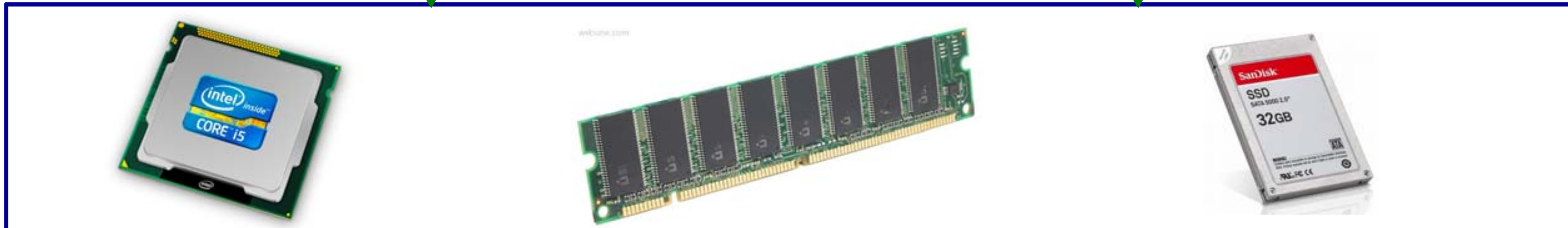
```
get_mpg:
    pushq   %rbp
    movq    %rsp, %rbp
    ...
    popq    %rbp
    ret
```

Machine code:

```
0111010000011000
100011010000010000000010
1000100111000010
110000011111101000011111
```

OS:

Computer system:



- Memory & data
- Integers & floats
- Machine code & C
- **x86 assembly**
- Procedures & stacks
- Arrays & structs
- Memory & caches
- Processes
- Virtual memory
- Memory allocation
- Java vs. C

x86 Topics for Today

- Registers
- Move instructions and operands
- Arithmetic operations
- Memory addressing modes
- `swap` example

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`)

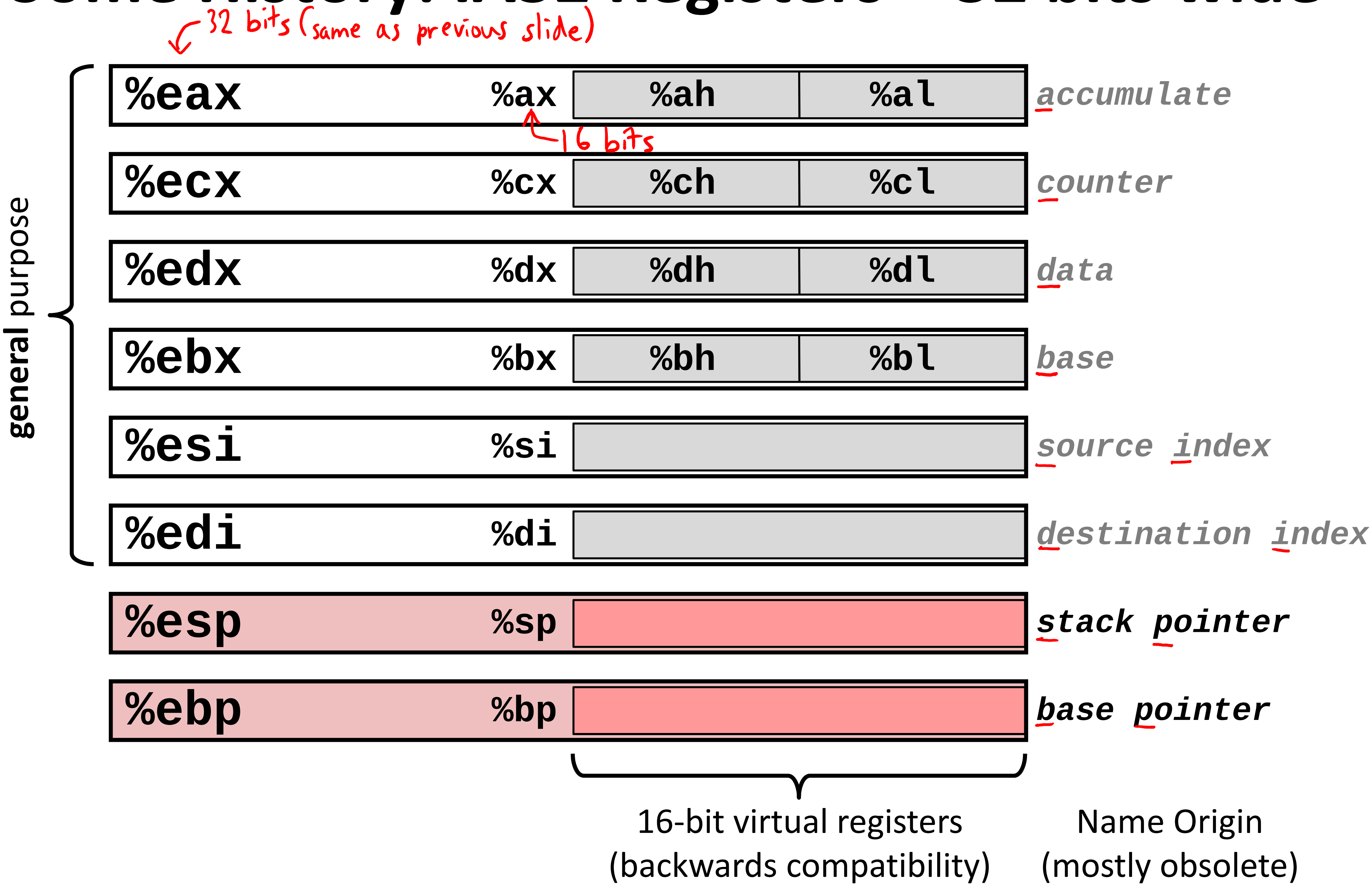
- Registers are at the heart of assembly programming
  - They are a precious commodity in all architectures, but *especially* x86

x86-64 Integer Registers – 64 bits wide

64 bits	32 bits	64 bits	32 bits
%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

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

Some History: IA32 Registers – 32 bits wide



x86-64 Assembly Data Types

- "Integer" data of 1, 2, 4, or 8 bytes
  - Data values
  - Addresses (untyped pointers)
- 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, …)
  - Probably won't have time to get into these ☹
- 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, …
  - ✗ "Intel": used by Intel documentation, Intel tools, …
  - Must know which you're reading

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

- ***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)`**
  - Various other "address modes"

take data in %rax, treat as address, pull data at that address

`%rax`
`%rcx`
`%rdx`
`%rbx`
`%rsi`
`%rdi`
`%rsp`
`%rbp`

stack pointer

`%rN` r8 - r15

Moving 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" 8 bits
- `movw src, dst`
  - Move 2-byte "**w**ord" 16 bits
- `movl src, dst`
  - Move 4-byte "**l**ong word" 32 bits
- `movq src, dst`
  - Move 8-byte "**q**uad word" 64 bits

movq Operand Combinations

x86		C
immediate	~	constant
register	~	variable
memory operand	~	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 movq (%rax), %rdx
② movq %rdx, (%rbx)

Memory vs. Registers

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

Some Arithmetic Operations

- 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`"?

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*	

operand size specifier

① moveq r1 r3 ; r3 = r1
② add q r2 r3 ; r3 = r1+r2

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(r)

by convention

```
long simple_arith(long x, long y)
{
  long t1 = x + y;       y = x+y
  long t2 = t1 * 3;      y = y*3
  return t2;
}
```

```
y += x;
y *= 3;
long r = y;
return r;
```

```
simple_arith:
           x      y
  addq    %rdi, %rsi    # y += x
                  y
  imulq     $3, %rsi    # y *= 3
            y     r
  movq    %rsi, %rax    # r = y
  ret
```

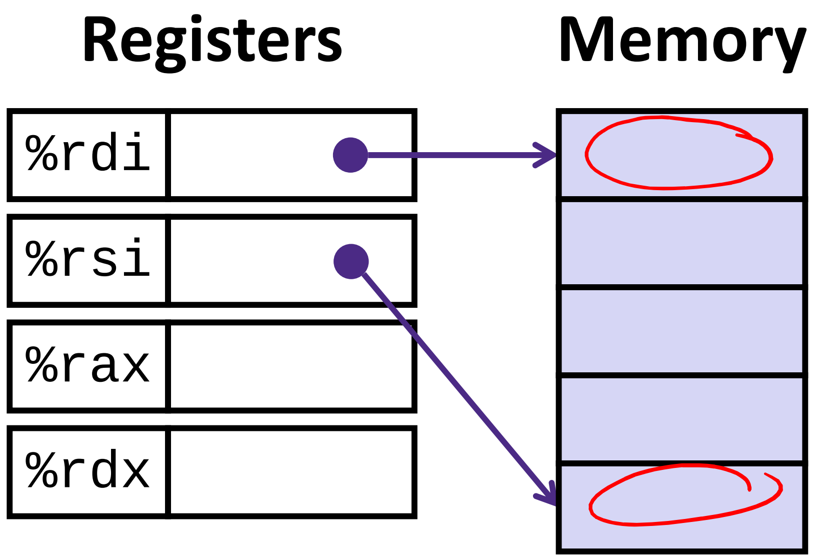
Example of Basic Addressing Modes

```
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
```

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()

initial values:

Registers

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

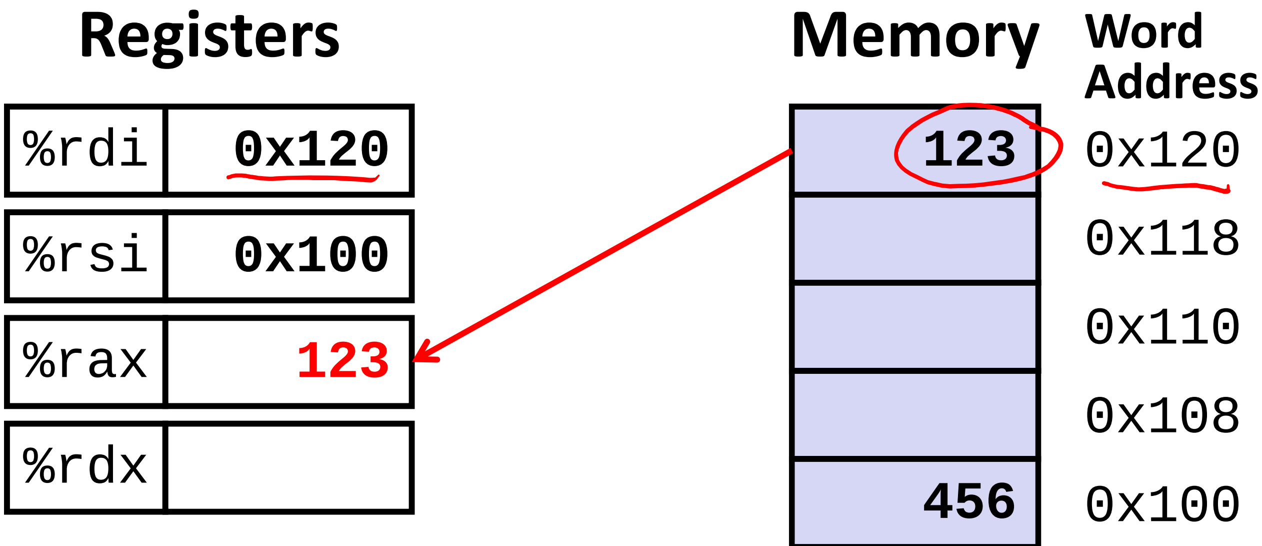
Memory

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

comment in x86

```
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
```

Understanding swap()



$123 (0x120)

```
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
	0x110
	0x108
456	0x100

$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()

Registers

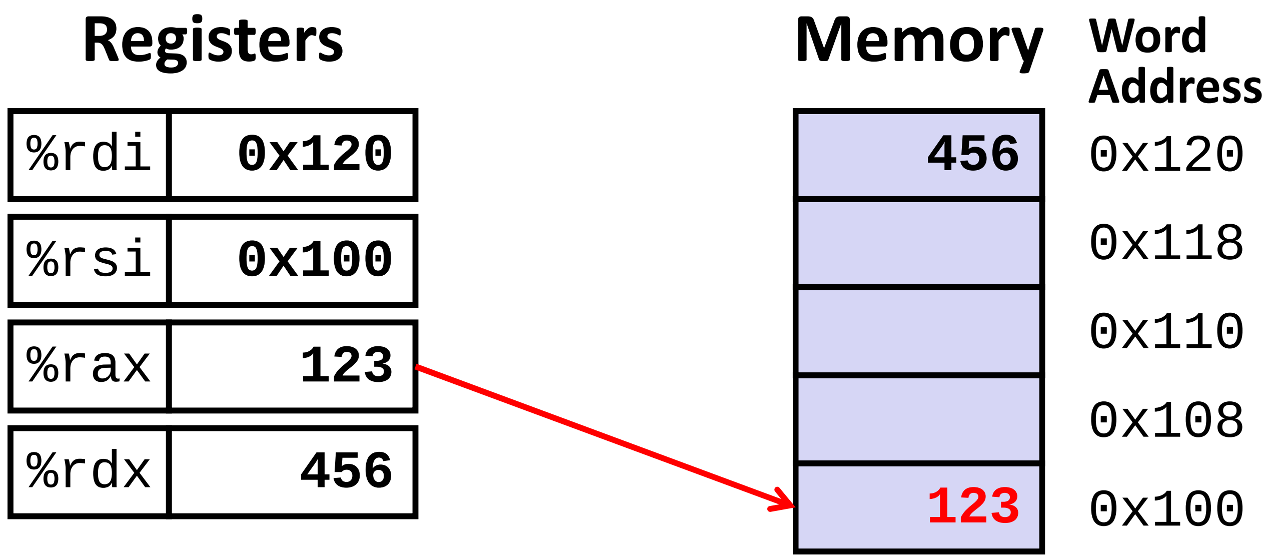
%rdi	0x120
%rsi	0x100
%rax	123
%rdx	456

Memory

	Word Address
456	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
```

Memory Addressing Modes: Basic

register name
treat memory like an array

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

data in register R

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

Immediate

- **Displacement:** D(R) Mem[Reg[R]+D]

offset

  - 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`

Complete Memory Addressing Modes

Pointer Arithmetic: ar[i] ⟺ *(ar + i) ⟺ Mem[ar + i * sizeof()]

- **General:**
  - `D(Rb,Ri,S)` Mem[Reg[Rb]+Reg[Ri]*S+D]

    ar i sizeof()
    - 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 CSPP Figure 3.3 on p.181)

  implicit values when not specified
  - `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

If omitted:
D = 0
Reg[Rb] = 0
Reg[Ri] = 0
S = 1

`%rdx`	`0xf000`
`%rcx`	`0x0100`

`D(Rb,Ri,S)` →
Mem[Reg[Rb]+Reg[Ri]*S+D]

Expression	Address Computation	Address
`0x8(%rdx)` (D, Rb)	0xf000 + 0*1 + 0x8	
`(%rdx,%rcx)` (Rb, Ri)	0xf000 + 0x0100*1 + 0	
`(%rdx,%rcx,4)` (Rb, Ri, S)	0xf000 + 0x0100*4 + 0	
`0x80(,%rdx,2)` (D, Ri, S)	0 + 0xf000*2 + 0x80	

same as shift left by 1

0x1e000

Address Computation Examples

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

D(Rb,Ri,S) →
Mem[Reg[Rb]+Reg[Ri]*S+D]

Expression	Address Computation	Address
0x8(%rdx)	0xf000 + 0x8	0xf008
(%rdx,%rcx)	0xf000 + 0x100	0xf100
(%rdx,%rcx,4)	0xf000 + 0x100*4	0xf400
0x80(,%rdx,2)	0xf000*2 + 0x80	0x1e080

Peer Instruction Question

- Which of the following statements is TRUE?
  - Vote at http://PollEv.com/justinh

(A) The program counter (%rip) is a register that we manually manipulate

not 1 of 16 available.
want %rip handled automatically

(B) There is only one way to compile a C program into assembly

absolutely not!

(C) Mem to Mem (src to dst) is the only disallowed operand combination

available operand types are Imm, Reg, Mem.
can't have Imm as dst.

(D) We can compute an address without using any registers

D(Rb,Ri,S) ⟶ just omit Rb and Ri
Example: $4() accesses address 4

Summary

- **Registers** are named locations in the CPU for holding and manipulating data
  - x86-64 uses 16 64-bit wide registers
- Assembly instructions have rigid form
  - Operands include immediates, registers, and data at specified memory locations
  - Many instruction variants based on size of data
- **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