Module III

Machine Language

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The concepts are based on Carnegie Mellon University course and the text-book, authored by Patterson and Hennesy

Today: Machine Programming I: Basics

- History of Intel processors and architectures
- C, assembly, machine code
- Assembly Basics: Registers, operands, move
- Arithmetic & logical operations

Data Format

Intel refer to a 16-bit data type as

Similarly, Intel refer to a 32-bit data type as

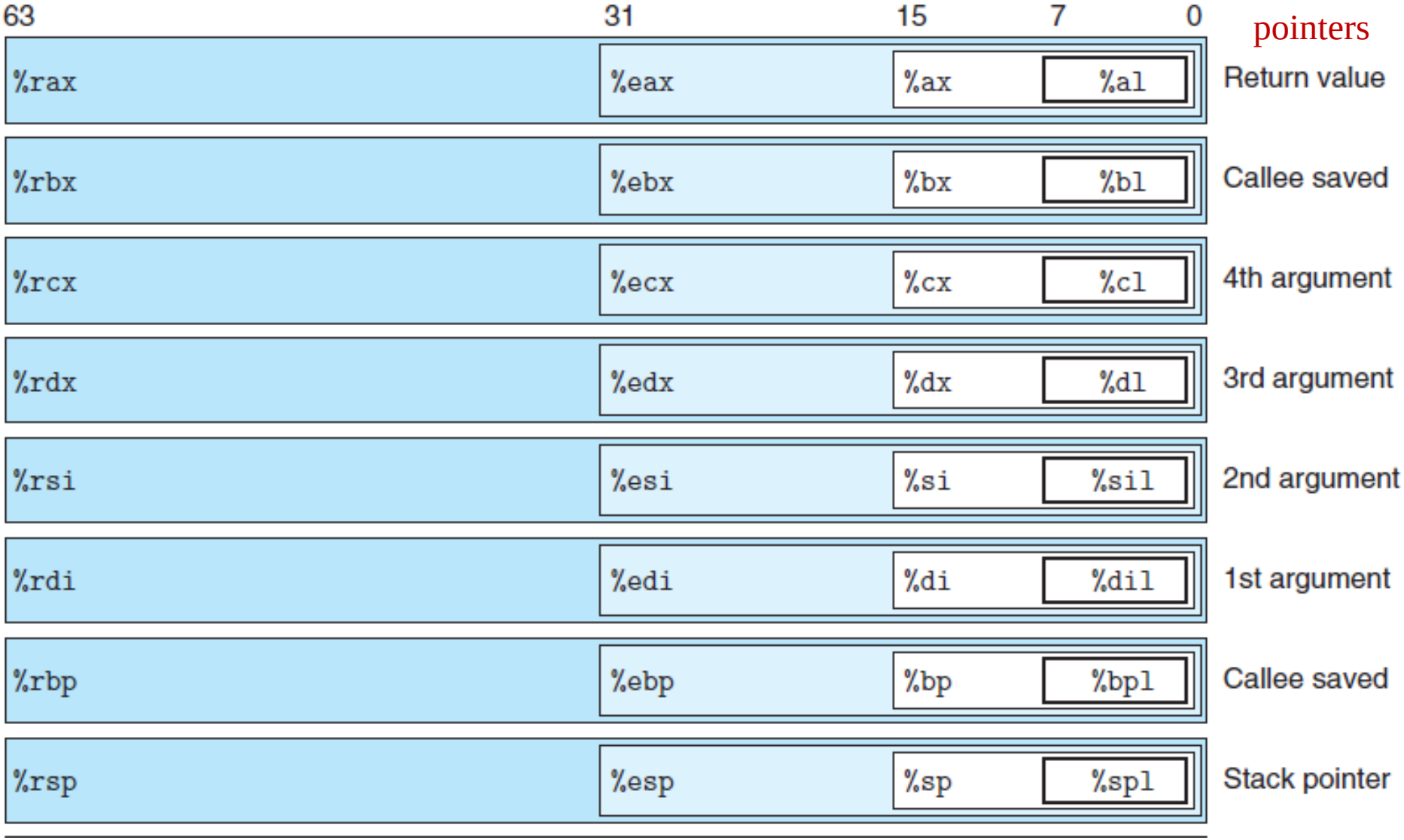
C declaration	Intel data type	Assembly-code suffix	Size (bytes)
`char`	Byte	`b`	1
`short`	Word	`w`	2
`int`	Double word	`l`	4
`long`	Quad word	`q`	8
`char *`	Quad word	`q`	8
`float`	Single precision	`s`	4
`double`	Double precision	`l`	8

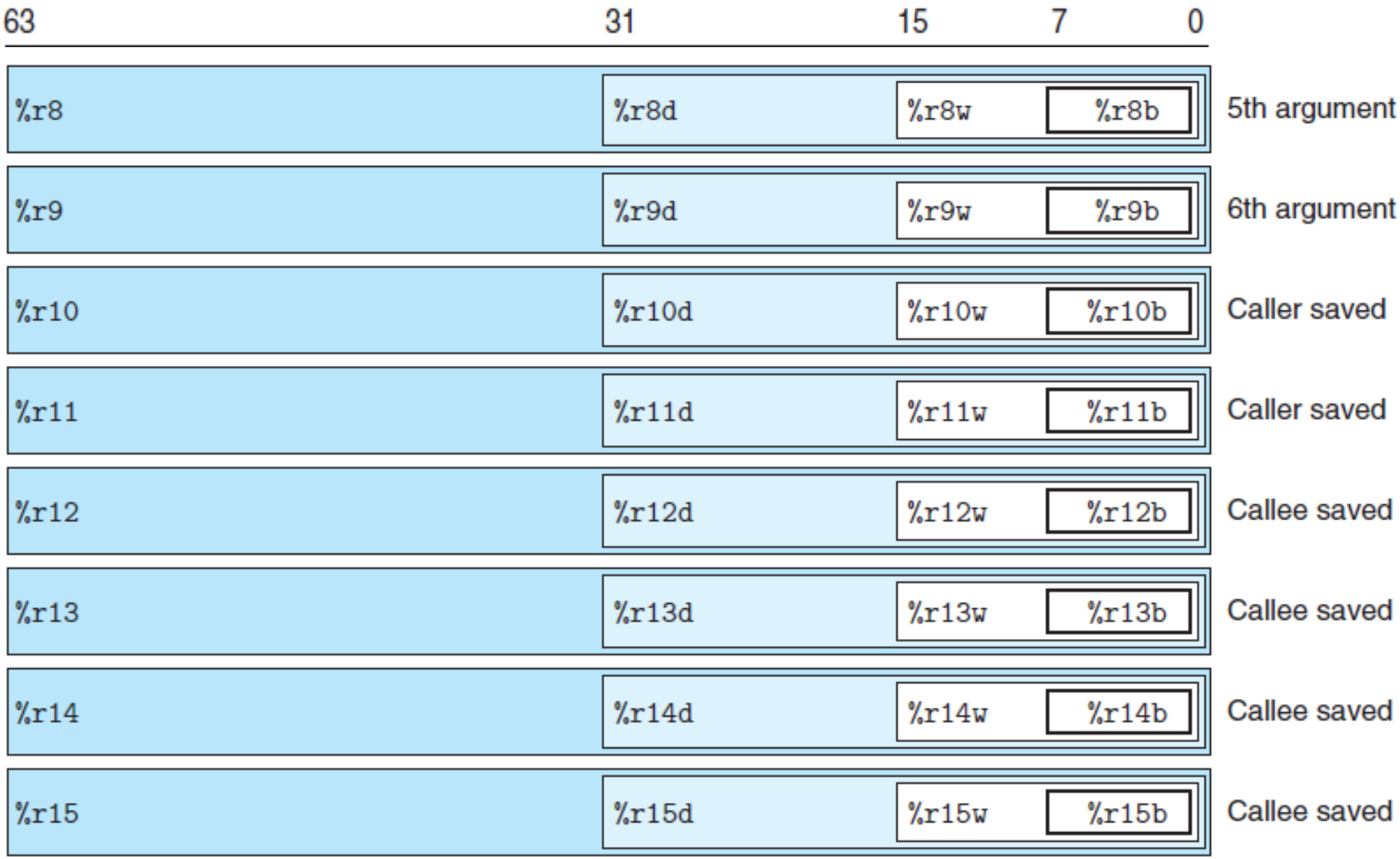
Figure 3.1 Sizes of C data types in x86-64. With a 64-bit machine, pointers are 8 bytes long.

Most assembly code instructions generated by GCC have a single character suffix denoting the size of the operand.

Accessing Information

X86-64 CPU contains a set of 16 general purpose registers, storing 64 bits values, These are used to store integer data and pointers




63
31
15
7
0
%r8
%r8d
%r8w
%r8b
5th argument
%r9
%r9d
%r9w
%r9b
6th argument
%r10
%r10d
%r10w
%r10b
Caller saved
%r11
%r11d
%r11w
%r11b
Caller saved
%r12
%r12d
%r12w
%r12b
Callee saved
%r13
%r13d
%r13w
%r13b
Callee saved
%r14
%r14d
%r14w
%r14b
Callee saved
%r15
%r15d
%r15w
%r15b
Callee saved

Operand Specifiers – Addressing Modes

- Most instructions have one or more *operands* specifying the source values to use
- Operand types: Immediate, Register, Memory

Type	Form	Operand value	Name
Immediate	$\$Imm$	Imm	Immediate
Register	r_a	$R[r_a]$	Register
Memory	Imm	$M[Imm]$	Absolute
Memory	(r_a)	$M[R[r_a]]$	Indirect
Memory	$Imm(r_b)$	$M[Imm + R[r_b]]$	Base + displacement
Memory	(r_b, r_i)	$M[R[r_b] + R[r_i]]$	Indexed
Memory	$Imm(r_b, r_i)$	$M[Imm + R[r_b] + R[r_i]]$	Indexed
Memory	$(, r_i, s)$	$M[R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(, r_i, s)$	$M[Imm + R[r_i] \cdot s]$	Scaled indexed
Memory	(r_b, r_i, s)	$M[R[r_b] + R[r_i] \cdot s]$	Scaled indexed
Memory	$Imm(r_b, r_i, s)$	$M[Imm + R[r_b] + R[r_i] \cdot s]$	Scaled indexed

Figure 3.3 **Operand forms.** Operands can denote immediate (constant) values, register values, or values from memory. The scaling factor s must be either 1, 2, 4, or 8.

Source value: To use performing an operation – It can be given as constant or read from the register or memory

Destination value: Location in to which place the result

Immediate is for constant values, typically, $ is used

Register : denotes the content of a register, among one of the sixteen

$R[r_a]$: used as reference – viewing the set of registers as an array

$M_b[Addr]$: Used for memory reference. Memory is large array of bytes. Denotes b-byte values stored in memory starting at address Addr

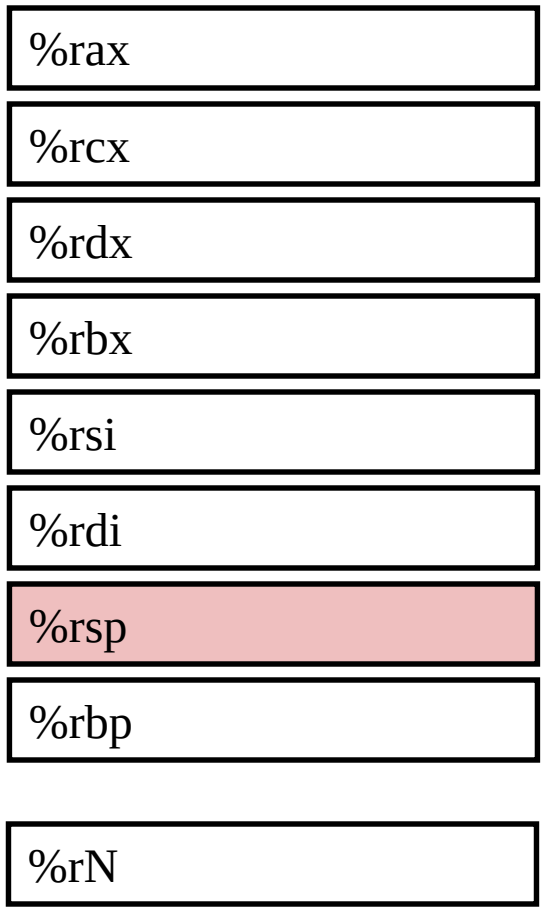
General form: Imm, base register, index register, and scale factor. Base and index must be 64-bit register, s must be 1, 2, 4, or 8.

Moving Data

- Moving Data

  movq *Source*, *Dest*:

- Operand Types
  - ***Immediate:*** Constant integer data
    - Example: **$0x400, $-533**
    - Like C constant, but prefixed with **'$'**
    - Encoded with 1, 2, or 4 bytes
  - ***Register:*** One of 16 integer registers
    - Example: **%rax, %r13**
    - But **%rsp** reserved for special use
    - Others have special uses for particular instructions
  - ***Memory:*** 8 consecutive bytes of memory at address given by register
    - Simplest example: **(%rax)**
    - Various other "address modes"



Example

Assume the following values are stored at the indicated memory addresses and registers:

Address	Value	Register	Value
0x100	0xFF	%rax	0x100
0x104	0xAB	%rcx	0x1
0x108	0x13	%rdx	0x3
0x10C	0x11		

Fill in the following table showing the values for the indicated operands:

Operand	Value
%rax	_____
0x104	_____
$0x108	_____
(%rax)	_____
4(%rax)	_____
9(%rax,%rdx)	_____
260(%rcx,%rdx)	_____
0xFC(,%rcx,4)	_____
(%rax,%rdx,4)	_____

Operand	Value	Comment
%rax	0x100	Register
0x104	0xAB	Absolute address
$0x108	0x108	Immediate
(%rax)	0xFF	Address 0x100
4(%rax)	0xAB	Address 0x104
9(%rax,%rdx)	0x11	Address 0x10C
260(%rcx,%rdx)	0x13	Address 0x108
0xFC(,%rcx,4)	0xFF	Address 0x100
(%rax,%rdx,4)	0x11	Address 0x10C

movq Operand Combinations

	Source	Dest	Src,Dest	C Analog
movq	*Imm*	*Reg*	movq $0x4,%rax	temp = 0x4;
		Mem	movq $-147,(%rax)	*p = -147;
	Reg	*Reg*	movq %rax,%rdx	temp2 = temp1;
		Mem	movq %rax,(%rdx)	*p = temp;
	Mem	*Reg*	movq (%rax),%rdx	temp = *p;

Cannot do memory-memory transfer with a single instruction

Date Movement Instructions

- For most cases, the mov instructions will only update the specific register bytes or memory locations indicated by the destination operand.
- The only exception is that when movl has a register as the destination, it will also set the high-order 4 bytes of the register to 0.
- This exception arises from the convention, adopted in x86-64, that any instruction that generates a 32-bit value for a register also sets the high-order portion of the register to 0.

Date Movement Instructions

`movabsq`	I, R	$R \leftarrow I$	Move absolute quad word

This instruction is for dealing with 64-bit immediate data.

The regular movq instruction can only have immediate source operands that can be represented as 32-bit two's-complement numbers. This value is then sign extended to produce the 64-bit value for the destination.

The movabsq instruction can have an arbitrary 64-bit immediate value as its source operand and can only have a register as a destination.

Aside Understanding how data movement changes a destination register

As described, there are two different conventions regarding whether and how data movement instructions modify the upper bytes of a destination register. This distinction is illustrated by the following code sequence:

```
1      movabsq $0x0011223344556677, %rax    %rax = 0011223344556677
2      movb    $-1, %al                     %rax = 0011223344556FF
3      movw    $-1, %ax                     %rax = 0011223344556FFF
4      movl    $-1, %eax                    %rax = 00000000FFFFFFFF
5      movq    $-1, %rax                    %rax = FFFFFFFFFFFFFFFF
```

In the following discussion, we use hexadecimal notation. In the example, the instruction on line 1 initializes register `%rax` to the pattern `0011223344556677`. The remaining instructions have immediate value −1 as their source values. Recall that the hexadecimal representation of −1 is of the form `FF`$\cdots$`F`, where the number of `F`'s is twice the number of bytes in the representation. The `movb` instruction (line 2) therefore sets the low-order byte of `%rax` to `FF`, while the `movw` instruction (line 3) sets the low-order 2 bytes to `FFFF`, with the remaining bytes unchanged. The `movl` instruction (line 4) sets the low-order 4 bytes to `FFFFFFFF`, but it also sets the high-order 4 bytes to `00000000`. Finally, the `movq` instruction (line 5) sets the complete register to `FFFFFFFFFFFFFFFF`.

Instruction	Effect	Description
MOVZ S, R	$R \leftarrow$ ZeroExtend(S)	Move with zero extension
`movzbw`		Move zero-extended byte to word
`movzbl`		Move zero-extended byte to double word
`movzwl`		Move zero-extended word to double word
`movzbq`		Move zero-extended byte to quad word
`movzwq`		Move zero-extended word to quad word

Figure 3.5 Zero-extending data movement instructions. These instructions have a register or memory location as the source and a register as the destination.

Instruction	Effect	Description
MOVS S, R	$R \leftarrow$ SignExtend(S)	Move with sign extension
`movsbw`		Move sign-extended byte to word
`movsbl`		Move sign-extended byte to double word
`movswl`		Move sign-extended word to double word
`movsbq`		Move sign-extended byte to quad word
`movswq`		Move sign-extended word to quad word
`movslq`		Move sign-extended double word to quad word
`cltq`	%rax $\leftarrow$ SignExtend(%eax)	Sign-extend %eax to %rax

Figure 3.6 Sign-extending data movement instructions. The MOVS instructions have a register or memory location as the source and a register as the destination. The `cltq` instruction is specific to registers %eax and %rax.

Practice Problem

For each of the following lines of assembly language, determine the appropriate instruction suffix based on the operands. (For example, `mov` can be rewritten as `movb`, `movw`, `movl`, or `movq`.)

```
mov__   %eax, (%rsp)
mov__   (%rax), %dx
mov__   $0xFF, %bl
mov__   (%rsp,%rdx,4), %dl
mov__   (%rdx), %rax
mov__   %dx, (%rax)
```

Practice Problem

Each of the following lines of code generates an error message when we invoke the assembler. Explain what is wrong with each line.

```
movb $0xF, (%ebx)
movl %rax, (%rsp)
movw (%rax),4(%rsp)
movb %al,%sl
movq %rax,$0x123
movl %eax,%rdx
movb %si, 8(%rbp)
```

Example

(b) Assembly code

```
    long exchange(long *xp, long y)
    xp in %rdi, y in %rsi
1   exchange:
2     movq    (%rdi), %rax     Get x at xp. Set as return value.
3     movq    %rsi, (%rdi)     Store y at xp.
4     ret                      Return.
```

Figure 3.7 C and assembly code for exchange routine. Registers %rdi and %rsi hold parameters xp and y, respectively.

Example

- xp is a pointer to a long integer
- y is a long integer itself
- Indicates that we should read the value stored in the location designated by xp and store it as a local variable named x – *pointer dereferencing*
- It writes the value of parameter y at the location designated by xp

(a) C code

```
long exchange(long *xp, long y)
{
    long x = *xp;
    *xp = y;
    return x;
}
```

(b) Assembly code

```
    long exchange(long *xp, long y)
    xp in %rdi, y in %rsi
1   exchange:
2     movq    (%rdi), %rax    Get x at xp. Set as return value.
3     movq    %rsi, (%rdi)    Store y at xp.
4     ret                     Return.
```

Figure 3.7 C and assembly code for exchange routine. Registers %rdi and %rsi hold parameters xp and y, respectively.

Pushing and Popping Stack Data

Instruction	Effect	Description
pushq S	R[%rsp] ← R[%rsp] − 8; M[R[%rsp]] ← S	Push quad word
popq D	D ← M[R[%rsp]]; R[%rsp] ← R[%rsp] + 8	Pop quad word

Figure 3.8 **Push and pop instructions.**

- Data movement operations: Push and Pop
- Stack plays a vital role in procedure calls
- Procedure call is an important and frequently used programming construct for a compiler
- Stack– a data structure—LIFO
- Program stack is stored in some region of the memory
- Top element has the lowest address
- %rsp holds the address of the top stack element

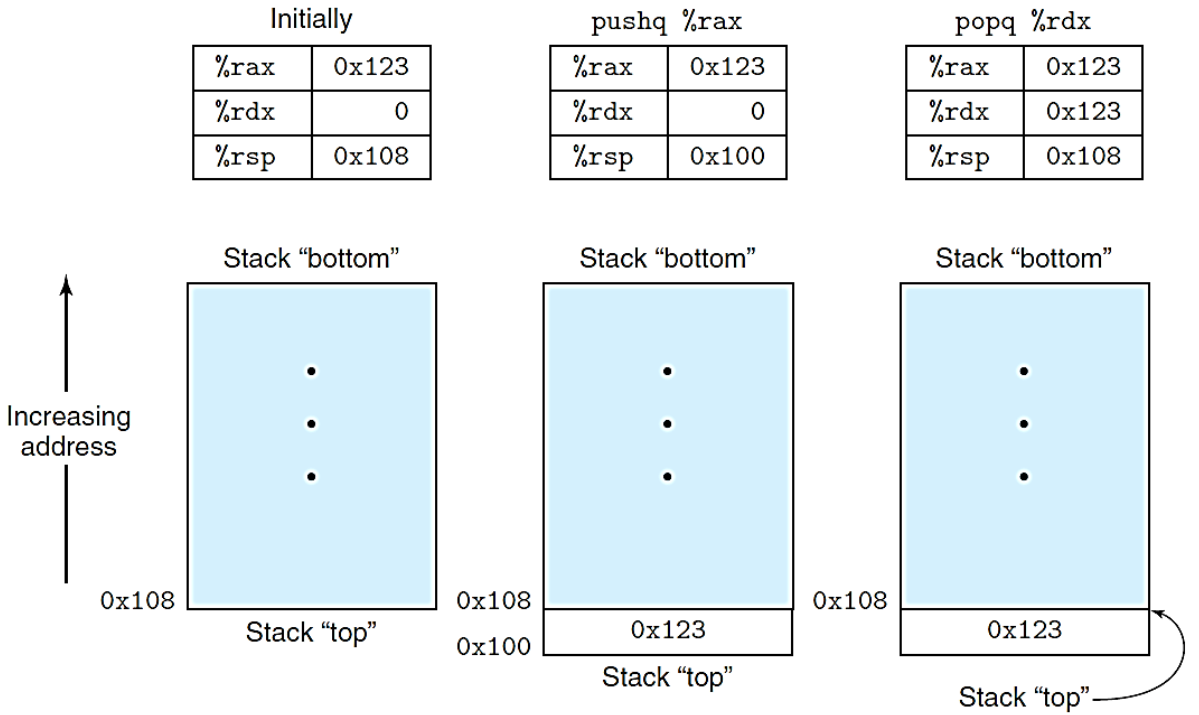


Figure 3.9 **Illustration of stack operation.** By convention, we draw stacks upside down, so that the "top" of the stack is shown at the bottom. With x86-64, stacks grow toward lower addresses, so pushing involves decrementing the stack pointer (register %rsp) and storing to memory, while popping involves reading from memory and incrementing the stack pointer.

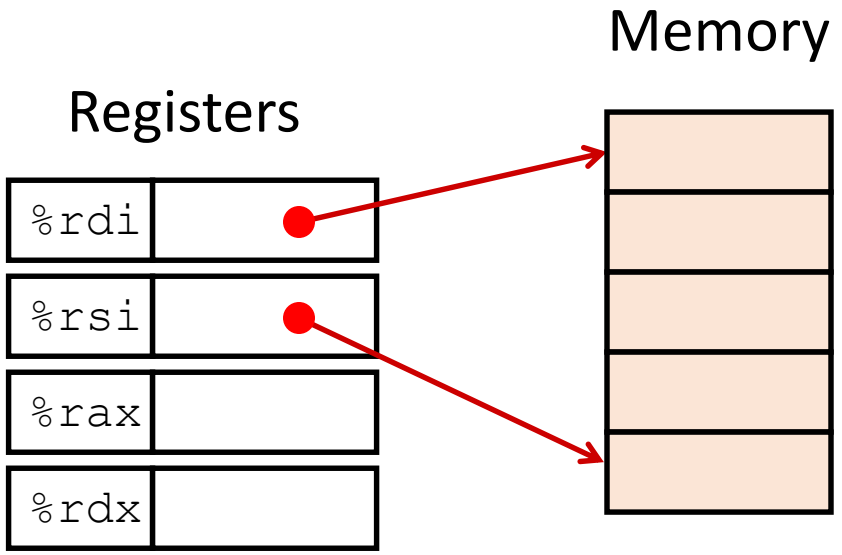
Example of Simple Addressing Modes

```
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;
}
```



Register	Value
%rdi	xp
%rsi	yp
%rax	t0
%rdx	t1

```
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

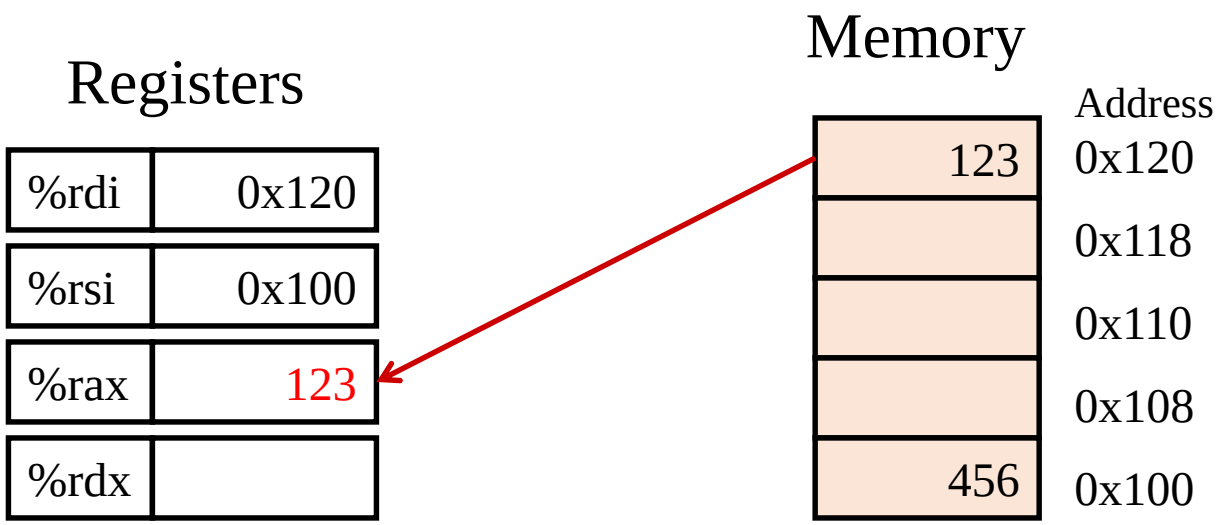
%rdi	0x120
%rsi	0x100
%rax	
%rdx	

Memory

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

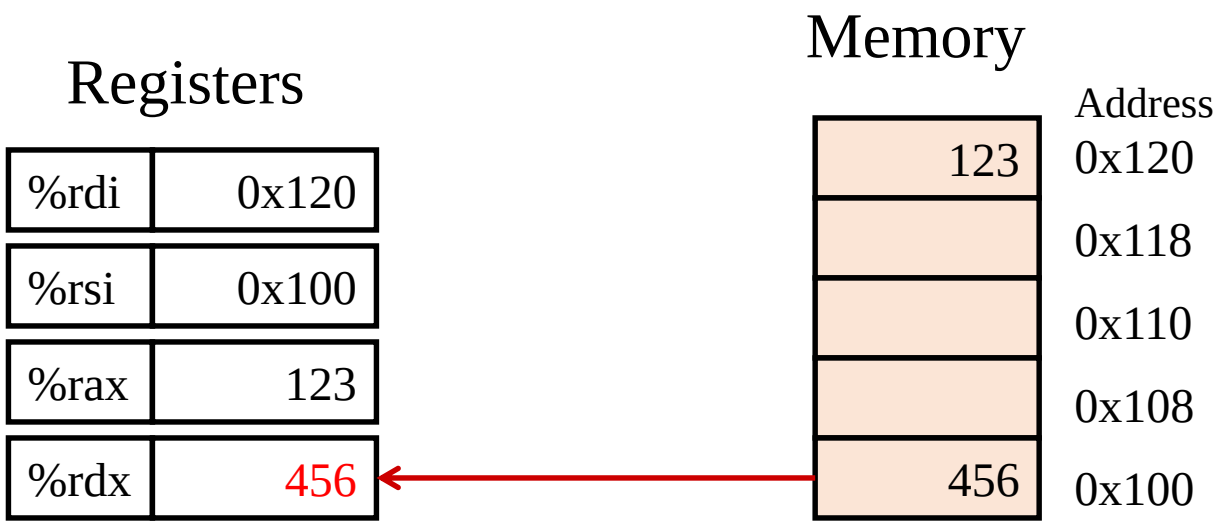
```
swap:
   movq    (%rdi), %rax  # t0 = *xp
   movq    (%rsi), %rdx  # t1 = *yp
   movq    %rdx, (%rdi)  # *xp = t1
   movq    %rax, (%rsi)  # *yp = t0
   ret
```

Understanding Swap()



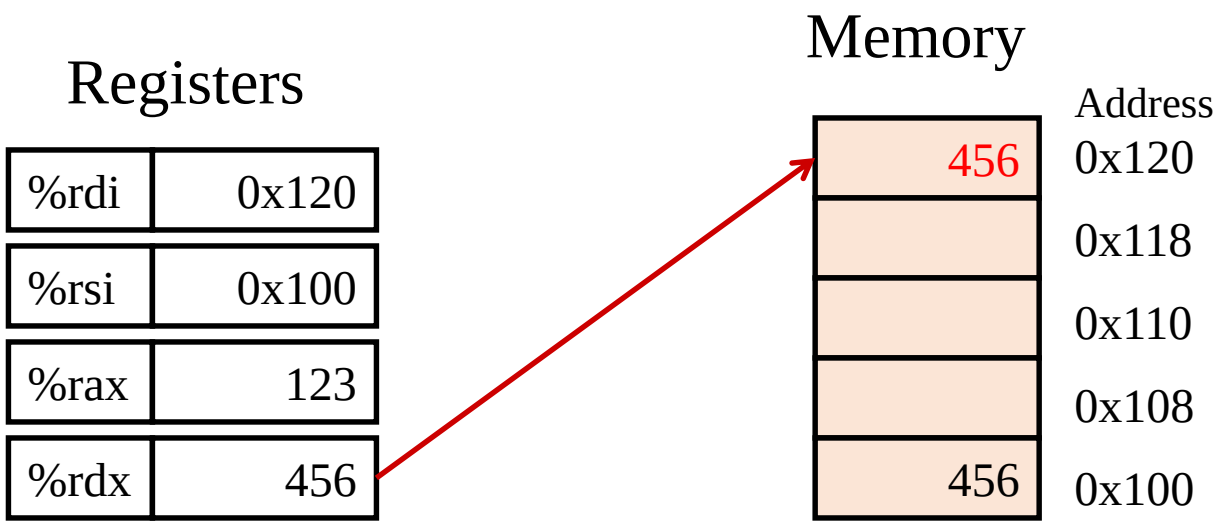

```
swap:
   movq    (%rdi), %rax  # t0 = *xp
   movq    (%rsi), %rdx  # t1 = *yp
   movq    %rdx, (%rdi)  # *xp = t1
   movq    %rax, (%rsi)  # *yp = t0
   ret
```

Understanding Swap()



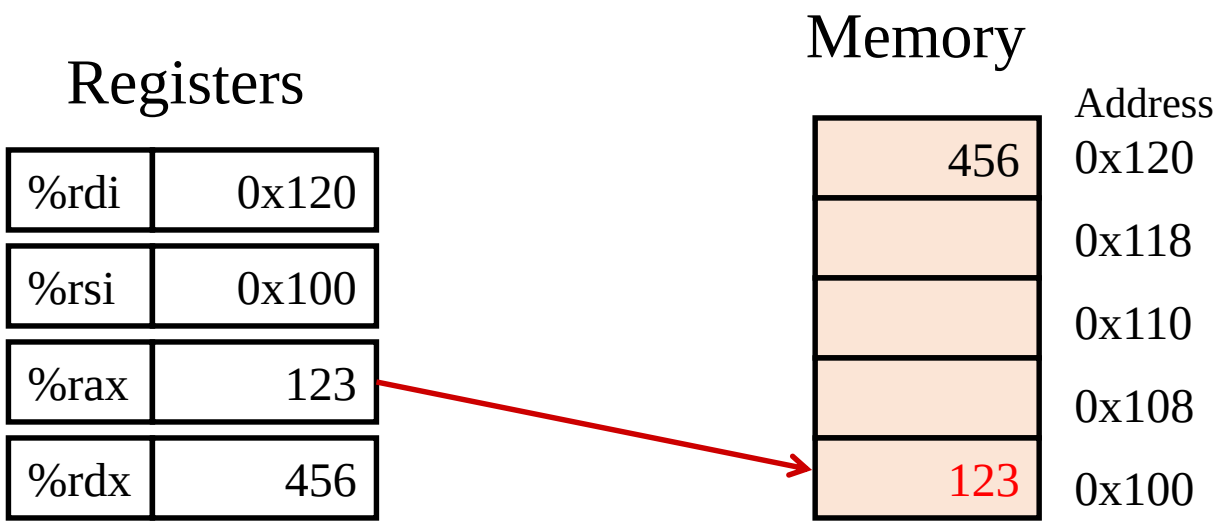

```
swap:
   movq    (%rdi), %rax  # t0 = *xp
   movq    (%rsi), %rdx  # t1 = *yp
   movq    %rdx, (%rdi)  # *xp = t1
   movq    %rax, (%rsi)  # *yp = t0
   ret
```

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
```