

CSCI 2021: Assembly Basics and x86-64

Chris Kauffman

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Logistics

Reading Bryant/O'Hallaron

- ▶ Now Ch 3.1-7: Assembly, Arithmetic, Control
- ▶ Later Ch 3.8-11: Arrays, Structs, Floats
- ▶ Any overview guide to x86-64 assembly instructions such as [Brown University's x64 Cheat Sheet](#)

Goals

- ▶ C Unions + FLOPS
- ▶ Assembly Basics
- ▶ x86-64 Overview

Lab / HW

- ▶ Lab05/HW05: Bit ops
- ▶ Lab06: GDB Basics
- ▶ HW06: Assembly Basics

P2: Due Thu 13-Oct

- ▶ Problem 1: Bit shift operations (50%)
- ▶ Problem 2: Puzzlebox via debugger (50% + makeup)

NOTE: Line Count Limits + Bit Shift Ops

GDB: The GNU Debugger

- ▶ Overview for C and Assembly Programs here:
<https://www-users.cs.umn.edu/~kauffman/2021/gdb>
- ▶ Most programming environments feature a Debugger
 - ▶ Java, Python, OCaml, etc.
- ▶ GDB works well C and Assembly programs
- ▶ Features in P2 (C programs) and P3 (Assembly Programs)
- ▶ P2 Demo has some basics for C programs including
 - ▶ TUI Mode
 - ▶ Breakpoint / Continue
 - ▶ Next / Step

The **Many** Assembly Languages

- ▶ Most **microprocessors** are created to understand a **binary machine language**
- ▶ Machine Language provides means to manipulate internal memory, perform arithmetic, etc.
- ▶ The Machine Language of one processor is **not understood** by other processors

MOS Technology 6502

- ▶ 8-bit operations, limited addressable memory, **1 general purpose register**, powered notable gaming systems in the 1980s
- ▶ Apple IIe, Atari 2600, Commodore
- ▶ Nintendo Entertainment System / Famicom

IBM Cell Microprocessor

- ▶ Developed in early 2000s, many cores (execution elements), many registers (32 on the PPE), large addressable space, fast multimedia performance, is a **pain** to program
- ▶ Playstation 3 and Blue Gene Supercomputer

Assemblers and Compilers



- ▶ **Compiler**: chain of tools that translate high level languages to lower ones, may perform optimizations
- ▶ **Assembler**: translates text description of the machine code to binary, formats for execution by processor, late compiler stage
- ▶ **Consequence**: The compiler can **generate assembly code**
- ▶ Generated assembly is a pain to read but is often quite fast
- ▶ **Consequence**: A compiler on an Intel chip can generate assembly code for a different processor, **cross compiling**

Our focus: The x86-64 Assembly Language

- ▶ x86-64 Targets Intel/AMD chips with 64-bit word size
Reminder: 64-bit “word size” \approx size of pointers/addresses
- ▶ Descended from IA32: Intel Architecture 32-bit systems
- ▶ IA32 descended from earlier 16-bit systems like Intel 8086
- ▶ There is a **LOT** of cruft in x86-64 for backwards compatibility
 - ▶ Can run compiled code from the 70's / 80's on modern processors without much trouble
 - ▶ x86-64 is not the assembly language you would design from scratch today
- ▶ Will touch on evolution of Intel Assembly as we move forward
- ▶ **Warning:** Lots of information available on the web for Intel assembly programming **BUT** some of it is dated, IA32 info which may not work on 64-bit systems

x86-64 Assembly Language Syntax(es)

- ▶ Different assemblers understand different syntaxes for the same assembly language
- ▶ GCC use the GNU Assembler (GAS, command 'as file.s')
- ▶ GAS and Textbook favor AT&T syntax so **we will too**
- ▶ NASM assembler favors Intel, may see this online

AT&T Syntax (Our Focus)

```
multstore:
    pushq    %rbx
    movq     %rdx, %rbx
    call     mult2@PLT
    movq     %rax, (%rbx)
    popq     %rbx
    ret
```

- ▶ Use of % to indicate registers
- ▶ Use of q/l/w/b to indicate 64 / 32 / 16 / 8-bit operands

Intel Syntax

```
multstore:
    push     rbx
    mov     rbx, rdx
    call     mult2@PLT
    mov     QWORD PTR [rbx], rax
    pop     rbx
    ret
```

- ▶ Register names are bare
- ▶ Use of QWORD etc. to indicate operand size

Generating Assembly from C Code

- ▶ `gcc -S file.c` will stop compilation at assembly generation
- ▶ Leaves assembly code in `file.s`
 - ▶ `file.s` and `file.S` conventionally assembly code though sometimes `file.asm` is used
- ▶ By default, compiler performs lots of optimizations to code
- ▶ `gcc -Og file.c`: disable optimizations to make it easier to debug, generated assembly is slightly more readable assembly

Example of Generating Assembly from C

```
>> cat exchange.c                                     # show C file to be translated
// exchange.c: sample C function
// to compile to assembly
long exchange(long *xp, long y){
    long x = *xp;
    *xp = y;
    return x;
}

>> gcc -Og -S exchange.c                             # Compile to show assembly
                                                    # -Og: debugging level optimization
                                                    # -S: only output assembly

>> cat exchange.s                                     # show assembly output
    .file      "exchange.c"
    .text
    .globl     exchange
    .type      exchange, @function

exchange:
.LFB0:
    .cfi_startproc
    movq       (%rdi), %rax                       # pointer derefs in assembly
    movq       %rsi, (%rdi)                       # uses registers
    ret
    .cfi_endproc

.LFE0:
    .size      exchange, .-exchange
    .ident     "GCC: (GNU) 11.1.0"
    .section    .note.GNU-stack,"",@progbits
```

gcc -Og -S mstore.c

```
> cat mstore.c                                # show a C file
long mult2(long a, long b);
void multstore(long x, long y, long *dest){
    long t = mult2(x, y);
    *dest = t;
}

> gcc -Og -S mstore.c                          # Compile to show assembly
                                              # -Og: debugging level optimization
                                              # -S: only output assembly

> cat mstore.s                                # show assembly output
    .file      "mstore.c"
    .text
    .globl    multstore                      # function symbol for linking
    .type     multstore, @function

multstore:                                    # beginning of mulstore function
.LFB0:
    .cfi_startproc                          # assembler directives
    pushq    %rbx                          # assembly instruction
    .cfi_def_cfa_offset 16                  # directives
    .cfi_offset 3, -16
    movq     %rdx, %rbx                    # assembly instructions
    call     mult2@PLT                     # function call
    movq     %rax, (%rbx)
    popq     %rbx
    .cfi_def_cfa_offset 8
    ret                                           # function return
    .cfi_endproc
```

Every Programming Language

Look for the following as it should almost always be there

- ☐ Comments
- ☐ Statements/Expressions
- ☐ Variable Types
- ☐ Assignment
- ☐ Basic Input/Output
- ☐ Function Declarations
- ☐ Conditionals (if-else)
- ☐ Iteration (loops)
- ☐ Aggregate data (arrays, structs, objects, etc)
- ☐ Library System

Exercise: Examine col_simple_asm.s

Take a simple sample problem to demonstrate assembly:

Computes Collatz Sequence starting at $n=10$:

*if n is ODD $n=n*3+1$; else $n=n/2$.*

*Return the number of steps to converge to 1 as the **return code** from `main()`*

The following codes solve this problem

Code	Notes
col_simple_asm.s	Hand-coded assembly for obvious algorithm Straight-forward reading
col_unsigned.c	Unsigned C version Generated assembly is reasonably readable
col_signed.c	Signed C version Generated assembly is ... interesting

- ▶ Kauffman will Compile/Run code
- ▶ Students should study the code and predict what lines do
- ▶ Illustrate tricks associated with gdb and assembly

Exercise: col_simple_asm.s

```
1  ### Compute Collatz sequence starting at 10 in assembly.
2  .section .text
3  .globl main
4  main:
5      movl    $0, %r8d        # int steps = 0;
6      movl    $10, %ecx       # int n = 10;
7  .LOOP:
8      cmpl    $1, %ecx        # while(n > 1){ // immediate must be first
9      jle     .END            #   n <= 1 exit loop
10     movl    $2, %esi        #   divisor in esi
11     movl    %ecx,%eax       #   prep for division: must use edx:eax
12     cqto    %esi            #   extend sign from eax to edx
13     idivl   %esi            #   divide edx:eax by esi
14                                     #   eax has quotient, edx remainder
15     cmpl    $1,%edx         #   if(n % 2 == 1) {
16     jne     .EVEN           #       not equal, go to even case
17  .ODD:
18     imull   $3, %ecx        #       n = n * 3
19     incl    %ecx            #       n = n + 1 OR n++
20     jmp     .UPDATE        #   }
21  .EVEN:
22     sarl    $1,%ecx         #       n = n / 2; via right shift
23  .UPDATE:
24     incl    %r8d            #   steps++;
25     jmp     .LOOP          #   }
26  .END:
27     movl    %r8d, %eax      # r8d is steps, move to eax for return value
28     ret
29
```

Answers: x86-64 Assembly Basics for AT&T Syntax

- ▶ *Comments* are one-liners starting with #
- ▶ *Statements*: each line does ONE thing, frequently text representation of an assembly instruction

```
movq    %rdx, %rbx    # move rdx register to rbx
```

- ▶ Assembler directives and labels are also possible:

```
.global  multstore      # notify linker of location multstore
multstore:              # label beginning of multstore section
    blah blah blah      # instructions in this this section
```

- ▶ *Variables*: mainly **registers**, also memory ref'd by registers
maybe some named global locations
- ▶ *Assignment*: instructions like movX that put move bits into registers and memory
- ▶ *Conditionals/Iteration*: assembly instructions that jump to code locations
- ▶ *Functions*: code locations that are **labeled** and global
- ▶ *Aggregate data*: none, use the stack/multiple registers
- ▶ *Library System*: link to other code

So what *are* these Registers?

- ▶ Memory locations directly wired to the CPU
- ▶ Usually very fast to access, faster than **main memory**
- ▶ Most instructions involve registers, access or change reg val

Example: Adding Together Integers

- ▶ Ensure registers have desired values in them
- ▶ Issue an addX instruction involving the two registers
- ▶ Result will be stored in a register

```
addl %eax, %ebx
```

```
# add ints in eax and ebx, store result in ebx
```

```
addq %rcx, %rdx
```

```
# add longs in rcx and rdx, store result in rdx
```

- ▶ Note instruction and register names indicate whether 32-bit int or 64-bit long are being added

x86-64 “General Purpose” Registers

Many “general purpose” registers have special purposes and conventions associated such as

- ▶ `%rax` | `%eax` | `%ax`
contains return value from functions
- ▶ `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`
contain first 6 arguments in function calls
- ▶ `%rsp` is top of the stack
- ▶ `%rbp` (base pointer) **may be the beginning of current stack** but is often optimized away by the compiler

64-bit	32-bit	16-bit	8-bit	Notes
<code>%rax</code>	<code>%eax</code>	<code>%ax</code>	<code>%al</code>	Return Val
<code>%rbx</code>	<code>%ebx</code>	<code>%bx</code>	<code>%bl</code>	
<code>%rcx</code>	<code>%ecx</code>	<code>%cx</code>	<code>%cl</code>	Arg 4
<code>%rdx</code>	<code>%edx</code>	<code>%dx</code>	<code>%dl</code>	Arg 3
<code>%rsi</code>	<code>%esi</code>	<code>%si</code>	<code>%sil</code>	Arg 2
<code>%rdi</code>	<code>%edi</code>	<code>%di</code>	<code>%dil</code>	Arg 1
<code>%rsp</code>	<code>%esp</code>	<code>%sp</code>	<code>%spl</code>	Stack Ptr
<code>%rbp</code>	<code>%ebp</code>	<code>%bp</code>	<code>%bpl</code>	Base Ptr?
<code>%r8</code>	<code>%r8d</code>	<code>%r8w</code>	<code>%r8b</code>	Arg 5
<code>%r9</code>	<code>%r9d</code>	<code>%r9w</code>	<code>%r9b</code>	Arg 6
<code>%r10</code>	<code>%r10d</code>	<code>%r10w</code>	<code>%r10b</code>	
<code>%r11</code>	<code>%r11d</code>	<code>%r11w</code>	<code>%r11b</code>	
<code>%r12</code>	<code>%r12d</code>	<code>%r12w</code>	<code>%r12b</code>	
<code>%r13</code>	<code>%r13d</code>	<code>%r13w</code>	<code>%r13b</code>	
<code>%r14</code>	<code>%r14d</code>	<code>%r14w</code>	<code>%r14b</code>	
<code>%r15</code>	<code>%r15d</code>	<code>%r15w</code>	<code>%r15b</code>	
Caller Save:		Restore after calling func		
Callee Save:		Restore before returning		

Register Naming Conventions

- ▶ AT&T syntax identifies registers with prefix %
- ▶ Naming convention is a historical artifact
- ▶ Originally 16-bit architectures in x86 had
 - ▶ General registers `ax, bx, cx, dx,`
 - ▶ Special Registers `si, di, sp, bp`
- ▶ *Extended* to 32-bit: `eax, ebx, ..., esi, edi, ...`
- ▶ Grew again to 64-bit: `rax, rbx, ..., rsi, rdi, ...`
- ▶ Added additional 64-bit regs `r8, r9, ..., r14, r15` with 32-bit `r8d, r9d, ...` and 16-bit `r8w, r9w, ...`
- ▶ Instructions must match registers sizes:
 - `addw %ax, %bx # words (16-bit)`
 - `addl %eax, %ebx # long word (32-bit)`
 - `addq %rax, %rbx # quad-word (64-bit)`
- ▶ When hand-coding assembly, easy to mess this up, assembler will error out

Hello World in x86-64 Assembly : Not that Easy

- ▶ Non-trivial in assembly because **output is involved**
 - ▶ Try writing `helloworld.c` without `printf()`
- ▶ Output is the business of the **operating system**, always a request to the almighty OS to put something somewhere
 - ▶ **Library call**: `printf("hello");` mangles some bits but eventually results with a ...
 - ▶ **System call**: Unix system call directly implemented in the OS **kernel**, puts bytes into files / onto screen as in
`write(1, buf, 5); // file 1 is screen output`

This gives us several options for hello world in assembly:

1. `hello_printf64.s`: via calling `printf()` which means the C standard library must be (painfully) linked
2. `hello64.s` via direct system `write()` call which means no external libraries are needed: OS knows how to write to files/screen. Use the 64-bit Linux calling convention.
3. `hello32.s` via direct system call using the older 32 bit Linux calling convention which “traps” to the operating system.

(Optional): The OS Privilege: System Calls

- ▶ Most interactions with the outside world happen via Operating System Calls (or just “system calls”)
- ▶ User programs indicate what service they want performed by the OS via making system calls
- ▶ System Calls differ for each language/OS combination
 - ▶ x86-64 Linux: set `%rax` to system call number, set other args in registers, issue `syscall`
 - ▶ IA32 Linux: set `%eax` to system call number, set other args in registers, issue an **interrupt**
 - ▶ C Code on Unix: make system calls via `write()`, `read()` and others (studied in CSCI 4061)
 - ▶ Tables of Linux System Call Numbers
 - ▶ 64-bit (335 calls)
 - ▶ 32-bit (190 calls)
 - ▶ Mac OS X: very similar to the above (it's a Unix)
 - ▶ Windows: use OS wrapper functions
- ▶ OS executes **privileged** code that can manipulate any part of memory, touch internal data structures corresponding to files, do other fun stuff discussed in CSCI 4061 / 5103

Basic Instruction Classes

- ▶ [x86 Assembly Guide from Yale](#) summarizes well though is 32-bit only, function calls different
- ▶ **Remember:** Goal is to understand assembly as a *target* for higher languages, not become expert “assemblists”
- ▶ Means we won’t hit all 5,038 pages of the [Intel x86-64 Manual](#)

Kind	Assembly Instructions
<i>Fundamentals</i>	
- Memory Movement	mov
- Stack manipulation	push, pop
- Addressing modes	(%eax), 12(%eax, %ebx) . . .
<i>Arithmetic/Logic</i>	
- Arithmetic	add, sub, mul, div, lea
- Bitwise Logical	and, or, xor, not
- Bitwise Shifts	sal, sar, shr
<i>Control Flow</i>	
- Compare / Test	cmp, test
- Set on result	set
- Jumps (Un)Conditional	jmp, je, jne, jl, jg, . . .
- Conditional Movement	cmovb, cmovg, . . .
<i>Procedure Calls</i>	
- Stack manipulation	push, pop
- Call/Return	call, ret
- System Calls	syscall
<i>Floating Point Ops</i>	
- FP Reg Movement	vmov
- Conversions	vcvts
- Arithmetic	vadd, vsub, vmul, vdiv
- Extras	vmins, vmaxs, sqrts

Data Movement: movX instruction

movX SOURCE, DEST # move source value to destination

Overview

- ▶ Moves data...
 - ▶ Reg to Reg
 - ▶ Mem to Reg
 - ▶ Reg to Mem
 - ▶ Imm to ...
- ▶ Reg: register
- ▶ Mem: main memory
- ▶ Imm: “immediate” value (constant) specified like
 - ▶ \$21 : decimal
 - ▶ \$0x2f9a : hexadecimal
 - ▶ **NOT** 1234 (mem adder)
- ▶ More info on operands next

Examples

64-bit quadword moves

```
movq $4, %rbx    # rbx = 4;
movq %rbx,%rax   # rax = rbx;
movq $10, (%rcx) # *rcx = 10;
```

32-bit longword moves

```
movl $4, %ebx    # ebx = 4;
movl %ebx,%eax   # eax = ebx;
movl $10, (%rcx) # *(int*)rcx=10;
```

Note variations

- ▶ movq for 64-bit (8-byte)
- ▶ movl for 32-bit (4-byte)
- ▶ movw for 16-bit (2-byte)
- ▶ movb for 8-bit (1-byte)

Operands and Addressing Modes

In many instructions like `movX`, operands can have a variety of forms called **addressing modes**, may include constants and memory addresses

Style	Address Mode	C-like	Notes
\$21 \$0xD2	immediate	21	value of constant like 21 or 0xD2 = 210
%rax (%rax)	register	rax	to/from register contents
8(%rax)	indirect	*rax	reg holds memory address, deref
4(%rdx)	displaced	*(rax+2) rdx->field	base plus constant offset, often used for struct field derefs
(%rax,%rbx)	indexed	*(rax+rbx) char_arr[rbx]	base plus offset in given reg actual value of rbx is used, NOT multiplied by sizeof()
(%rax,%rbx,4) (%rax,%rbx,8)	scaled index	rax[rbx] rax[rbx]	like array access with sizeof(..)=4 "" with sizeof(..)=8
1024	absolute	...	Absolute address #1024 Rarely used

Exercise: Show movX Instruction Execution

Code movX_exercise.s

```
movl $16, %eax
movl $20, %ebx
movq $24, %rbx
## POS A

movl %eax,%ebx
movq %rcx,%rax
## POS B

movq $45, (%rdx)
movl $55, 16(%rdx)
## POS C

movq $65, (%rcx,%rbx)
movq $3,%rbx
movq $75, (%rcx,%rbx,8)
## POS D
```

Registers/Memory

INITIAL

-----+-----+-----			
REG	%rax		0
	%rbx		0
	%rcx		#1024
	%rdx		#1032
-----+-----+-----			
MEM	#1024		35
	#1032		25
	#1040		15
	#1048		5
-----+-----+-----			

Lookup...

May need to look up addressing conventions for things like...

```
movX %y,%x    # reg y to reg x
movX $5, (%x)  # 5 to address in %x
```

Answers Part 1/2: movX Instruction Execution

INITIAL		movl \$16, %eax movl \$20, %ebx movq \$24, %rbx ## POS A		movl %eax,%ebx movq %rcx,%rax #WARNING! ## POS B	
-----+-----		-----+-----		-----+-----	
REG VALUE		REG VALUE		REG VALUE	
%rax 0		%rax 16		%rax #1024	
%rbx 0		%rbx 24		%rbx 16	
%rcx #1024		%rcx #1024		%rcx #1024	
%rdx #1032		%rdx #1032		%rdx #1032	
-----+-----		-----+-----		-----+-----	
MEM VALUE		MEM VALUE		MEM VALUE	
#1024 35		#1024 35		#1024 35	
#1032 25		#1032 25		#1032 25	
#1040 15		#1040 15		#1040 15	
#1048 5		#1048 5		#1048 5	
-----+-----		-----+-----		-----+-----	

#!: On 64-bit systems, ALWAYS use a 64-bit reg name like %rdx and movq to copy memory addresses; using smaller name like %edx will miss half the memory addressing leading to major memory problems

Answers Part 2/2: movX Instruction Execution

```
movl %eax,%ebx
movq %rcx,%rax #!
```

POS B

REG	VALUE
%rax	#1024
%rbx	16
%rcx	#1024
%rdx	#1032
MEM	VALUE
#1024	35
#1032	25
#1040	15
#1048	5

```
movq $45, (%rdx)
               #1032
movq $55, 16(%rdx)
               16+#1032=#1048
```

POS C

REG	VALUE
%rax	#1024
%rbx	16
%rcx	#1024
%rdx	#1032
MEM	VALUE
#1024	35
#1032	45
#1040	15
#1048	55

```
movq $65, (%rcx,%rbx)
               #1024+16 = #1040
movq $3,%rbx
movq $75, (%rcx,%rbx,8)
               #1024 + 3*8 = #1048
```

POS D

REG	VALUE
%rax	#1024
%rbx	3
%rcx	#1024
%rdx	#1032
MEM	VALUE
#1024	35
#1032	45
#1040	65
#1048	75

`gdb` Assembly: Examining Memory

`gdb` commands `print` and `x` allow one to print/examine memory of interest. Try on `movX_exercises.s`

```
(gdb) tui enable           # TUI mode
(gdb) layout asm           # assembly mode
(gdb) layout reg           # show registers
(gdb) stepi                # step forward by single Instruction
(gdb) print $rax           # print register rax
(gdb) print *($rdx)        # print memory pointed to by rdx
(gdb) print (char *) $rdx  # print as a string (null terminated)
(gdb) x $r8                # examine memory at address in r8
(gdb) x/3d $r8             # same but print as 3 4-byte decimals
(gdb) x/6g $r8             # same but print as 6 8-byte decimals
(gdb) x/s $r8              # print as a string (null terminated)
(gdb) print *((int*) $rsp) # print top int on stack (4 bytes)
(gdb) x/4d $rsp            # print top 4 stack vars as ints
(gdb) x/4x $rsp            # print top 4 stack vars as ints in hex
```

Many of these tricks are needed to debug assembly.

Register Size and Movement

- ▶ Recall %rax is 64-bit register, %eax is lower 32 bits of it
- ▶ Data movement involving small registers **may NOT overwrite** higher bits in extended register

- ▶ Moving data to low 32-bit regs automatically zeros high 32-bits

```
movabsq $0x1122334455667788, %rax # 8 bytes to %rax
movl $0xAABBCCDD, %eax # 4 bytes to %eax
## %rax is now 0x00000000AABBCCDD
```

- ▶ Moving data to other small regs DOES NOT ALTER high bits

```
movabsq $0x1122334455667788, %rax # 8 bytes to %rax
movw $0xAABB, %ax # 2 bytes to %ax
## %rax is now 0x112233445566AABB
```

- ▶ Gives rise to two other families of movement instructions for moving little registers (X) to big (Y) registers, see movz_examples.s

```
## movzXY move zero extend, movsXY move sign extend
movabsq $0x112233445566AABB,%rdx
movzwl %dx,%rax # %rax is 0x000000000000AABB
movswl %dx,%rax # %rax is 0xFFFFFFFFFFFFAABB
```

Exercise: movX differences in Memory

Instr	# bytes
movb	1 byte
movw	2 bytes
movl	4 bytes
movq	8 bytes

Show the result of each of the following copies to main memory in sequence.

```
movl    %eax,    (%rsi) #1
movq    %rax,    (%rsi) #2
movb    %cl,     (%rsi) #3
movw    %cx,     2(%rsi) #4
movl    %ecx,    4(%rsi) #5
```

INITIAL

-----+-----	
REG	
rax	0x00000000DDCCBBAA
rcx	0x000000000000FFEE
rsi	#1024
-----+-----	
MEM	
#1024	0x00
#1025	0x11
#1026	0x22
#1027	0x33
#1028	0x44
#1029	0x55
#1030	0x66
#1031	0x77
#1032	0x88
#1033	0x99
-----+-----	

Answers: movX to Main Memory 1/2

-----+-----	movl	%eax, (%rsi)	#1 4 bytes rax -> #1024
REG	movq	%rax, (%rsi)	#2 8 bytes rax -> #1024
rax 0x00000000DDCCBBAA	movb	%cl, (%rsi)	#3 1 byte rcx -> #1024
rcx 0x000000000000FFEE	movw	%cx, 2(%rsi)	#4 2 bytes rcx -> #1026
rsi #1024	movl	%ecx, 4(%rsi)	#5 4 bytes rcx -> #1028
-----+-----			

INITIAL	#1 movl %eax, (%rsi)	#2 movq %rax, (%rsi)	#3 movb %cl, (%rsi)
-----+-----	-----+-----	-----+-----	-----+-----
MEM	MEM	MEM	MEM
#1024 0x00	#1024 0xAA	#1024 0xAA	#1024 0xEE
#1025 0x11	#1025 0xBB	#1025 0xBB	#1025 0xBB
#1026 0x22	#1026 0xCC	#1026 0xCC	#1026 0xCC
#1027 0x33	#1027 0xDD	#1027 0xDD	#1027 0xDD
#1028 0x44	#1028 0x44	#1028 0x00	#1028 0x00
#1029 0x55	#1029 0x55	#1029 0x00	#1029 0x00
#1030 0x66	#1030 0x66	#1030 0x00	#1030 0x00
#1031 0x77	#1031 0x77	#1031 0x00	#1031 0x00
#1032 0x88	#1032 0x88	#1032 0x88	#1032 0x88
#1033 0x99	#1033 0x99	#1033 0x99	#1033 0x99
-----+-----	-----+-----	-----+-----	-----+-----

Answers: movX to Main Memory 2/2

-----+-----	movl	%eax, (%rsi)	#1 4 bytes rax -> #1024
REG	movq	%rax, (%rsi)	#2 8 bytes rax -> #1024
rax 0x00000000DDCCBBAA	movb	%cl, (%rsi)	#3 1 byte rcx -> #1024
rcx 0x000000000000FFEE	movw	%cx, 2(%rsi)	#4 2 bytes rcx -> #1026
rsi #1024	movl	%ecx, 4(%rsi)	#5 4 bytes rcx -> #1028
-----+-----			

#3

movb %cl, (%rsi)

-----+-----
MEM
#1024 0xEE
#1025 0xBB
#1026 0xCC
#1027 0xDD
#1028 0x00
#1029 0x00
#1030 0x00
#1031 0x00
#1032 0x88
#1033 0x99
-----+-----

#4

movw %cx, 2(%rsi)

-----+-----
MEM
#1024 0xEE
#1025 0xBB
#1026 0xEE
#1027 0xFF
#1028 0x00
#1029 0x00
#1030 0x00
#1031 0x00
#1032 0x88
#1033 0x99
-----+-----

#5

movl %ecx, 4(%rsi)

-----+-----
MEM
#1024 0xEE
#1025 0xBB
#1026 0xEE
#1027 0xFF
#1028 0xEE
#1029 0xFF
#1030 0x00
#1031 0x00
#1032 0x88
#1033 0x99
-----+-----

addX : A Quintessential ALU Instruction

`addX B, A` $\# A = A+B$ ► Addition represents most 2-operand ALU instructions well

OPERANDS:

`addX %reg, %reg`
`addX (%mem), %reg`
`addX %reg, (%mem)`
`addX $con, %reg`
`addX $con, (%mem)`

- Second operand A is modified by first operand B, No change to B
- Variety of register, memory, constant combinations honored
- `addX` has variants for each register size: `addq`, `addl`, `addw`, `addb`

$\#$ No `mem+mem` or `con+con`

EXAMPLES:

<code>addq %rdx, %rcx</code>	$\# rcx = rcx + rdx$
<code>addl %eax, %ebx</code>	$\# ebx = ebx + eax$
<code>addq \$42, %rdx</code>	$\# rdx = rdx + 42$
<code>addl (%rsi), %edi</code>	$\# edi = edi + *rsi$
<code>addw %ax, (%rbx)</code>	$\# *rbx = *rbx + ax$
<code>addq \$55, (%rbx)</code>	$\# *rbx = *rbx + 55$

`addl (%rsi,%rax,4), %edi` $\# edi = edi + rsi[rax] \text{ (int)}$

Exercise: Addition

Show the results of the following addX/movX ops at each of the specified positions

```
addq $1,%rcx      # con + reg
addq %rbx,%rax     # reg + reg
## POS A

addq (%rdx),%rcx   # mem + reg
addq %rbx,(%rdx)   # reg + mem
addq $3,(%rdx)     # con + mem
## POS B

addl $1,(%r8,%r9,4) # con + mem
addl $1,%r9d       # con + reg
addl %eax,(%r8,%r9,4) # reg + mem
addl $1,%r9d       # con + reg
addl (%r8,%r9,4),%eax # mem + reg
## POS C
```

INITIAL		
-----+-----		
REGS		
%rax		15
%rbx		20
%rcx		25
%rdx		#1024
%r8		#2048
%r9		0
-----+-----		
MEM		
#1024		100
...		...
#2048		200
#2052		300
#2056		400
-----+-----		

Answers: Addition

INITIAL		POS A		POS B		POS C	
-----+-----		-----+-----		-----+-----		-----+-----	
REG		REG		REG		REG	
%rax	15	%rax	35	%rax	35	%rax	435
%rbx	20	%rbx	20	%rbx	20	%rbx	20
%rcx	25	%rcx	26	%rcx	126	%rcx	126
%rdx	#1024	%rdx	#1024	%rdx	#1024	%rdx	#1024
%r8	#2048	%r8	#2048	%r8	#2048	%r8	#2048
%r9	0	%r9	0	%r9	0	%r9	2
-----+-----		-----+-----		-----+-----		-----+-----	
MEM		MEM		MEM		MEM	
#1024	100	#1024	100	#1024	123	#1024	123
...
#2048	200	#2048	200	#2048	200	#2048	201
#2052	300	#2052	300	#2052	300	#2052	335
#2056	400	#2056	400	#2056	400	#2056	400
-----+-----		-----+-----		-----+-----		-----+-----	

```
addq $1,%rcx
addq %rbx,%rax
```

```
addq (%rdx),%rcx
addq %rbx, (%rdx)
addq $3, (%rdx)
```

```
addl $1, (%r8,%r9,4)
addl $1,%r9d
addl %eax, (%r8,%r9,4)
addl $1,%r9d
addl (%r8,%r9,4), %eax
```

The Other ALU Instructions

- ▶ Most ALU instructions follow the same pattern as addX: two operands, second gets changed.
- ▶ Some one operand instructions as well.

Instruction	Name	Effect	Notes
addX B, A	Add	$A = A + B$	Two Operand Instructions
subX B, A	Subtract	$A = A - B$	
imulX B, A	Multiply	$A = A * B$	<i>Has a limited 3-arg variant</i>
andX B, A	And	$A = A \& B$	
orX B, A	Or	$A = A B$	Arithmetic: Sign carry Logical: Zero carry
xorX B, A	Xor	$A = A \wedge B$	
salX B, A	Shift Right	$A = A \ll B$	
shlX B, A		$A = A \ll B$	
sarX B, A		$A = A \gg B$	
shrX B, A		$A = A \gg B$	
incX A	Increment	$A = A + 1$	One Operand Instructions
decX A	Decrement	$A = A - 1$	
negX A	Negate	$A = -A$	
notX A	Complement	$A = \sim A$	

leax: Load Effective Address

- ▶ Memory addresses must often be loaded into registers
- ▶ Often done with a leax, usually leaq in 64-bit platforms
- ▶ Sort of like “address-of” op & in C but a bit more general

INITIAL

-----+-----	
REG	VAL
rax	0
rcx	2
rdx	#1024
rsi	#2048
-----+-----	
MEM	
#1024	15
#1032	25
...	
#2048	200
#2052	300
#2056	400
-----+-----	

leax_examples.s:

```
movq 8(%rdx),%rax      # rax = *(rdx+1) = 25
leaq 8(%rdx),%rax      # rax = rdx+1      = #1032
movl (%rsi,%rcx,4),%eax # rax = rsi[rcx]    = 400
leaq (%rsi,%rcx,4),%rax # rax = &(rsi[rcx]) = #2056
```

Compiler sometimes uses leax for multiplication as it is usually faster than imulx but less readable.

```
# Odd Collatz update n = 3*n+1
#READABLE with imulx      #OPTIMIZED with leax:
imul $3,%eax              leal 1(%eax,%eax,2),%eax
addl $1,%eax
# eax = eax*3 + 1          # eax = eax + 2*eax + 1,
# 3-4 cycles               # 1 cycle
# gcc, you are so clever...
```

Division: It's a Pain (1/2)

- ▶ Unlike other ALU operations, `idivX` operation has some special rules
- ▶ Dividend must be in the `rax / eax / ax` register
- ▶ Sign extend to `rdx / edx / dx` register with `cqto`
- ▶ `idivX` takes one **register** argument which is the divisor
- ▶ At completion
 - ▶ `rax / eax / ax` holds quotient (integer part)
 - ▶ `rdx / edx / dx` holds the remainder (leftover)

```
### division.s:
movl    $15, %eax    # set eax to int 15
cqto    # extend sign of eax to edx
## combined 64-bit register %edx:%eax is
## now 0x00000000 0000000F = 15
movl    $2, %esi     # set esi to 2
idivl   %esi         # divide combined register by 2
## 15 div 2 = 7 rem 1
## %eax == 7, quotient
## %edx == 1, remainder
```

Compiler avoids division whenever possible: compile `col_unsigned.c` and `col_signed.c` to see some tricks.

Division: It's a Pain (2/2)

- ▶ When performing division on 8-bit or 16-bit quantities, use instructions to sign extend small reg to all rax register

```
### division with 16-bit shorts from division.s
movq $0,%rax      # set rax to all 0's
movq $0,%rdx      # set rdx to all 0's
                  # rax = 0x00000000 00000000
                  # rdx = 0x00000000 00000000
movw $-17, %ax    # set ax to short -17
                  # rax = 0x00000000 0000FFEF
                  # rdx = 0x00000000 00000000
cwtl              # "convert word to long" sign extend ax to eax
                  # rax = 0x00000000 FFFFFFFF
                  # rdx = 0x00000000 00000000
cltq              # "convert long to quad" sign extend eax to rax
                  # rax = 0xFFFFFFFF FFFFFFFF
                  # rdx = 0x00000000 00000000
cqto              # sign extend rax to rdx
                  # rax = 0xFFFFFFFF FFFFFFFF
                  # rdx = 0xFFFFFFFF FFFFFFFF
movq $3, %rcx     # set rcx to long 3
idivq %rcx        # divide combined rax/rdx register by 3
                  # rax = 0xFFFFFFFF FFFFFFFB = -5 (quotient)
                  # rdx = 0xFFFFFFFF FFFFFFFE = -2 (remainder)
```