CSCI 2021: Assembly Basics and x86-64

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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

- ▶ Assembly Basics
- ▶ x86-64 Overview

Lab / HW

- ▶ Lab06: GDB Basics
- ▶ HW06: Assembly Basics

Project 2: Due Tue 3/2

- ▶ Problem 1: Bit shift operations (50%)
- ▶ Problem 2: Puzzlebox via debugger (50% + makeup)
- ▶ Update Testing files for Problem 1:
  test_prob1.org,
  test_batt_update.c,
  batt_sim.c

NOTE: Line on Count Limits

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
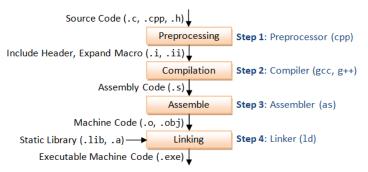
MOS Technology 6502

- ▶ 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, large addressable space, fast multimedia performance, is a **pain** to program
- ▶ Playstation 3 and Blue Gene Supercomputer

Assemblers and Compilers

Source Code (.c, .cpp, .h) →
Step 1: Preprocessor (cpp) — Preprocessing
Include Header, Expand Macro (.i, .ii) →
Step 2: Compiler (gcc, g++) — Compilation
Assembly Code (.s) →
Step 3: Assembler (as) — Assemble
Machine Code (.o, .obj) →
Static Library (.lib, .a) → Linking — **Step 4**: Linker (ld)
Executable Machine Code (.exe) →

- ▶ **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" ≈ size of pointers/addresses
- ▶ Descended 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

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 vesion
	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                    #   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:                          #   else{
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:

```
        .globl  multstore   # notify linker of location multstore
  multstore:                # beginning of multstore section
        blah blah blah
```

▶ *Variables*: **registers** and memory, maybe some named locations
▶ *Assignment*: instructions that put bits in registers/memory
▶ *Functions*: code locations that are **labeled** and global
▶ *Conditionals/Iteration*: assembly instructions that jump to code locations
▶ *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 memory, on-chip memory (not RAM)
- ▶ Most instructions involve changes to registers

Example: Adding Together Integers

- ▶ Ensure registers have desired values in them
- ▶ Issue an add 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

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,r8w...
- ▶ 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

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

Hello World in x86-64 Assembly

- ▶ 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.

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 (328 calls)
    - ▶ 32-bit (190 calls)
  - ▶ Mac OS X: very similar to the above (it's a Unix)
  - ▶ Windows: use OS wrapper functions
- ▶ OS executes **priveleged** 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
Fundamentals	
- Memory Movement	`mov`
- Stack manipulation	`push,pop`
- Addressing modes	`(%eax),$12(%eax,%ebx)...`
Arithmetic/Logic	
- Arithmetic	`add,sub,mul,div,lea`
- Bitwise Logical	`and,or,xor,not`
- Bitwise Shifts	`sal,sar,shr`
Control Flow	
- Compare / Test	`cmp,test`
- Set on result	`set`
- Jumps (Un)Conditional	`jmp,je,jne,jl,jg,...`
- Conditional Movement	`cmove,cmovg,...`
Procedure Calls	
- Stack manipulation	`push,pop`
- Call/Return	`call,ret`
- System Calls	`syscall`
Floating Point Ops	
- 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, (%ecx)  # *ecx = 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	immediate	21	value of constant like 21
$0xD2			or 0xD2 = 210
%rax	register	rax	to/from register contents
(%rax)	indirect	*rax	reg holds memory address, deref
8(%rax)	displaced	*(rax+2)	base plus constant offset,
-4(%rax)		*(rax-1)	C examples presume sizeof(..)=4
(%rax,%rbx)	indexed	*(rax+rbx)	base plus offset in given reg
			actual value of rbx is used, NOT
			multiplied by sizeof()
(%rax,%rbx,4)	scaled index	rax[rbx]	like array access with sizeof(..)=4
(%rax,%rbx,8)		rax[rbx]	"" 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
```

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Answers Part 1/2: movX Instruction Execution

```
                        movl $16, %eax
                        movl $20, %ebx     movl %eax,%ebx
                        movq $24, %rbx     movq %rcx,%rax #WARNING!
INITIAL                 ## POS A           ## 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 `movq` move for memory addresses; using smaller `movl` 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)
movq $55,16(%rdx)
 ## 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)
movq $3,%rbx
movq $75,(%rcx,%rbx,8)
 ## 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 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
movzwq %dx,%rax     # %rax is 0x000000000000AABB
movswq %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
|-----+--------------------|
```

```
                     #1                    #2                    #3
INITIAL              movl %eax,(%rsi)      movq %rax,(%rsi)      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                        #4                        #5
movb %cl,(%rsi)           movw %cx,2(%rsi)          movl %ecx,4(%rsi)
|-------+------|          |-------+------|          |-------+------|
| MEM   |      |          | MEM   |      |          | MEM   |      |
| #1024 | 0xEE |          | #1024 | 0xEE |          | #1024 | 0xEE |
| #1025 | 0xBB |          | #1025 | 0xBB |          | #1025 | 0xBB |
| #1026 | 0xCC |          | #1026 | 0xEE |          | #1026 | 0xEE |
| #1027 | 0xDD |          | #1027 | 0xFF |          | #1027 | 0xFF |
| #1028 | 0x00 |          | #1028 | 0x00 |          | #1028 | 0xEE |
| #1029 | 0x00 |          | #1029 | 0x00 |          | #1029 | 0xFF |
| #1030 | 0x00 |          | #1030 | 0x00 |          | #1030 | 0x00 |
| #1031 | 0x00 |          | #1031 | 0x00 |          | #1031 | 0x00 |
| #1032 | 0x88 |          | #1032 | 0x88 |          | #1032 | 0x88 |
| #1033 | 0x99 |          | #1033 | 0x99 |          | #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

```
No mem+mem or con+con
```

- addX has variants for each register size: addq, addl, addw, addb

```
EXAMPLES
 addq %rdx,  %rcx      # rcx = rcx + rdx
 addl %eax,  %ebx      # ebx = ebx + eax
 addq $42,   %rdx      # rdx = rdx + 42
 addl (%rsi),%edi      # edi = edi + *rsi
 addw %ax,   (%rbx)    # *rbx = *rbx + ax
 addq $55,   (%rbx)    # *rbx = *rbx + 55

 addl (%rsi,%rax,4),%rdi   # rdi = rdi+rsi[rax] (int)
```

Exercise: Addition

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

```
addq $1,%rcx        # con + reg         INITIAL
addq %rbx,%rax       # reg + reg         |-------+-------|
## POS A                                 | REGS  |       |
                                         | %rax  |    15 |
addq (%rdx),%rcx     # mem + reg         | %rbx  |    20 |
addq %rbx,(%rdx)     # reg + mem         | %rcx  |    25 |
addq $3,(%rdx)       # con + mem         | %rdx  | #1024 |
## POS B                                 | %r8   | #2048 |
                                         | %r9   |     0 |
addl $1,(%r8,%r9,4)       # con + mem    |-------+-------|
addl $1,%r9d              # con + reg    | MEM   |       |
addl %eax,(%r8,%r9,4)     # reg + mem    | #1024 |   100 |
addl $1,%r9d              # con + reg    | ...   |   ... |
addl (%r8,%r9,4),%eax     # mem + reg    | #2048 |   200 |
## POS C                                 | #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 (%rdx),%rcx    addl $1,(%r8,%r9,4)
addq %rbx,%rax    addq %rbx,(%rdx)    addl $1,%r9d
                  addq $3,(%rdx)      addl %eax,(%r8,%r9,4)
                                      addl $1,%r9d
                                      addl (%r8,%r9,4),%eax
```

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The Other ALU Instructions

- ▶ Most ALU instructions follow the same patter 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	*Has a limited 3-arg variant*
andX B, A	And	A = A & B	
orX B, A	Or	A = A | B	
xorX B, A	Xor	A = A ^ B	
salX B, A	Shift Left	A = A << B	
shlX B, A		A = A << B	
sarX B, A	Shift Right	A = A >> B	Arithmetic: Sign carry
shrX B, A		A = A >> B	Logical: Zero carry
incX A	Increment	A = A + 1	One Operand Instructions
decX A	Decrement	A = A - 1	
negX A	Negate	A = -A	
notX A	Complement	A = ~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 FFFFFFEF
                    # rdx = 0x00000000 00000000
cltq                # "convert long to quad" sign extend eax to rax
                    # rax = 0xFFFFFFFF FFFFFFEF
                    # rdx = 0x00000000 00000000
cqto                # sign extend rax to rdx
                    # rax = 0xFFFFFFFF FFFFFFEF
                    # 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)
```