CMSC216: Assembly Basics and x86-64

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Logistics

Reading Bryant/O'Hallaron

- Skim Ch 2.7-8: Floating Point Layout
- 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

Assignments

- P2: Due Fri 14-Mar-2025
- Lab06: Assembly Coding
- HW06: Assembly Debugging

Both relevant to P3

Goals

- Floating Point Layout (20min)
- Assembly Basics
- x86-64 Overview

Announcements

Midterm Grades Posted / Grade Calculator Up

See Post 493 for info and summary statistics; overall things look good; use Grade Calculator to track your progress

Midterm Feedback Survey

Results being processed by Prof K, likely post summary stats and responses on Fri 14-Mar

Project 3 Looming

- Problem 1: Convert P2 Scale functions to assembly
- Problem 2: Puzzlebin, like Puzzlebox but no source code, use disassembled binary to trace what inputs are required to earn points

Will post before spring break BUT no expectation that students work on it over the break; ~14 days after break before the deadline.

Today is a Double Dot Day - Participate and earn 2 Dots

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

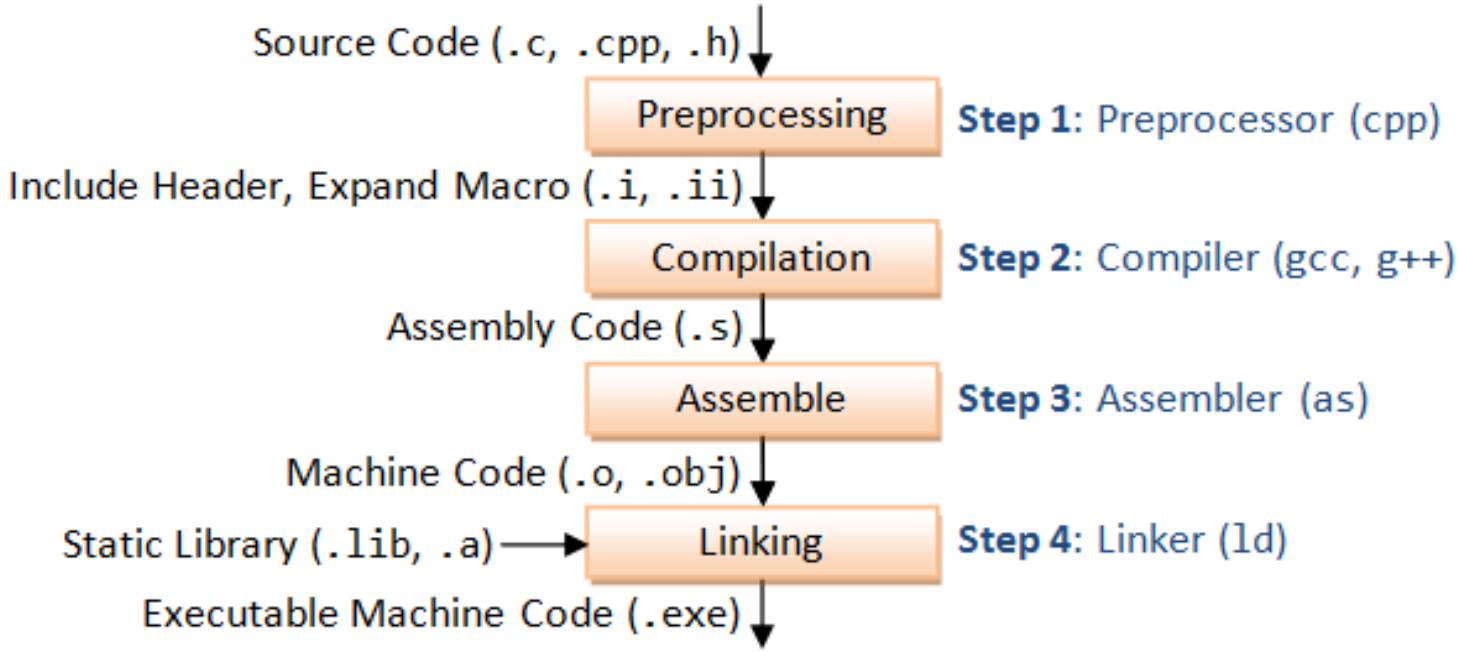
MOS Technology 6502

- 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, 64-bit, 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" ≈ size of pointers/addresses
- Lineage of x86 family
  - 1970s: 16-bit systems like Intel 8086
  - 1990s: IA32 (Intel 32-bit systems like 80386 and 80486)
  - 2000s: x86-64 (64-bit extension by AMD)
- x86-64 is backwards compatibility, consequently much cruft
  - Can run compiled code from the 70's / 80's on modern processors without much trouble BUT means 50-year-old instructions must be preserved
  - x86-64 is not the assembly language you would design from scratch today, it's the assembly you have to code against
  - RISC-V is a new assembly language that is "clean" as it has no history to support (and few CPUs run it)
- 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 generates code that is often difficult for humans to interpret, may include re-arrangements, "conservative" compatibility assembly, etc. increasing size of assembly considerably
- `gcc -Og file.c`: optimize for debugging, generally makes it easier to read generated assembly, aligns somewhat more closely to C code

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){           # function to translate
  long x = *xp;                            # involves pointer deref
  *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:                                  # beginning of exchange function
.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 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:

```
.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 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

- Return Value: `%rax` / `%eax` / `%ax`
- Function Args 1 to 6: `%rdi`, `%rsi`, `%rdx`, `%rcx`, `%r8`, `%r9`
- Stack Pointer (top of stack): `%rsp`
- Old Code Base Pointer: `%rbp`, historically start of current stack frame but is not used that way in modern codes

Note: There are also Special Registers like `%rip` and `%eflags` which we will discuss later.

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			

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 Eight 64-bit regs `r8,r9,...,r14,r15` with 32-bit portion `r8d,r9d,...`, 16-bit `r8w,r9w...`, etc.
- Instructions must match registers sizes:

```
addw %ax,  %bx  #      word (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 **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

- **Remember:** Goal is to understand assembly as a *target* for higher languages, not become expert "assemblists"
- Means we won't hit all 4,834 pages of the Intel x86-64 Manual
- Brown University's x64 Cheat Sheet has a good overview
- x86 Assembly Guide from Yale is also good but is limited to 32-bit coverage

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/copy source value to dest
```

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)   # *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`	register	`rax`	to/from register contents
`(%rax)`	indirect	`*rax`	reg holds memory address, deref
`8(%rax)` `4(%rdx)`	displaced	`*(rax+2)` `rdx->field`	base plus constant offset, often used for strcut 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

```
                    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 |
|------+-------|    |------+-------|    |------+-------|
```

`#WARNING!`: 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 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 Main 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
movw   4(%rsi), %ax   #6
```

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 | 0x0000000000000FEE |  movw   %cx,  2(%rsi) #4 2 bytes rcx -> #1026
| rsi |              #1024 |  movl   %ecx, 4(%rsi) #5 4 bytes rcx -> #1028
|-----+--------------------|  movw   4(%rsi), %ax  #6 2 bytes #1024 -> rax
```

INITIAL

MEM	
#1024	0x00
#1025	0x11
#1026	0x22
#1027	0x33
#1028	0x44
#1029	0x55
#1030	0x66
#1031	0x77
#1032	0x88
#1033	0x99

#1
movl %eax,(%rsi)

MEM	
#1024	0xAA
#1025	0xBB
#1026	0xCC
#1027	0xDD
#1028	0x44
#1029	0x55
#1030	0x66
#1031	0x77
#1032	0x88
#1033	0x99

#2
movq %rax,(%rsi)

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

#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

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
|-----+--------------------|  movw   4(%rsi), %ax  #6 2 bytes #1024 -> rax
```

#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

#6
`movw 4(%rsx),%ax`

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

rax	0x00000000DDCCFFEE

addX : A Quintessential ALU Instruction

```
 addX  B, A     # A = A+B

OPERANDS:
 addX %reg,  %reg
 addX (%mem),%reg
 addX %reg,  (%mem)
 addX $con,  %reg
 addX $con,  (%mem)

# No mem+mem or con+con

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),%edi    # edi = edi+rsi[rax] (int)
```

- Addition represents most 2-operand ALU instructions well
- 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`

Optional 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	
REG	
%rax	15
%rbx	20
%rcx	25
%rdx	#1024
%r8	#2048
%r9	0
MEM	
#1024	100
...	...
#2048	200
#2052	300
#2056	400

POS A	
REG	
%rax	35
%rbx	20
%rcx	26
%rdx	#1024
%r8	#2048
%r9	0
MEM	
#1024	100
...	...
#2048	200
#2052	300
#2056	400

POS B	
REG	
%rax	35
%rbx	20
%rcx	126
%rdx	#1024
%r8	#2048
%r9	0
MEM	
#1024	123
...	...
#2048	200
#2052	300
#2056	400

POS C	
REG	
%rax	435
%rbx	20
%rcx	126
%rdx	#1024
%r8	#2048
%r9	2
MEM	
#1024	123
...	...
#2048	201
#2052	335
#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 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`	`B` is constant or `%cl` reg
`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
```

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

- `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                    # extends 0 sign bit (positive) to edx
## combined 64-bit register %edx:%eax is
## eax: 0x00000000 0000000F = 15
## exx: 0x00000000 00000000 =  0
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

# answer in eax, return
ret
```

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)
```