Princeton University

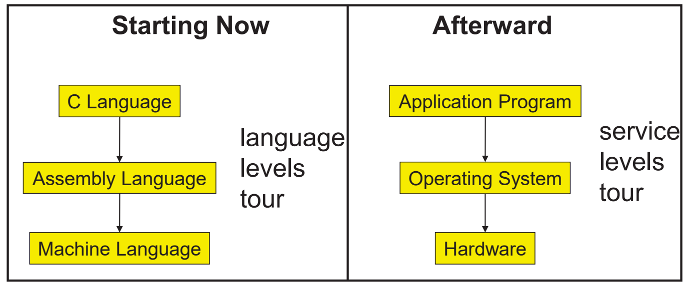
Computer Science 217: Introduction to Programming Systems

Assembly Language:
Part 1

Context of this Lecture

First half lectures: "Programming in the large"

Second half lectures: "Under the hood"



Goals of this Lecture

Help you learn:

- Language levels
- The basics of x86-64 **architecture**
  - Enough to understand x86-64 assembly language
- The basics of x86-64 **assembly language**
  - Instructions to define global data
  - Instructions to transfer data and perform arithmetic

Lectures vs. Precepts

Approach to studying assembly language:

Precepts	Lectures
Study **complete** pgms	Study **partial** pgms
Begin with **small** pgms; proceed to **large** ones	Begin with **simple** constructs; proceed to **complex** ones
Emphasis on **writing** code	Emphasis on **reading** code

Agenda

Language Levels

Architecture

Assembly Language: Defining Global Data

Assembly Language: Performing Arithmetic

High-Level Languages

Characteristics

- Portable
  - To varying degrees
- Complex
  - One statement can do much work
- Expressive
  - To varying degrees
  - Good (code functionality / code size) ratio
- Human readable

```
count = 0;
while (n>1)
{  count++;
   if (n&1)
      n = n*3+1;
   else
      n = n/2;
}
```

Machine Languages

Characteristics

- Not portable
  - Specific to hardware
- Simple
  - Each instruction does a simple task
- Not expressive
  - Each instruction performs little work
  - Poor (code functionality / code size) ratio
- Not human readable
  - Requires lots of effort!
  - Requires tool support

```
0000 0000 0000 0000 0000 0000 0000 0000
0000 0000 0000 0000 0000 0000 0000 0000
9222 9120 1121 A120 1121 A121 7211 0000
0000 0001 0002 0003 0004 0005 0006 0007
0008 0009 000A 000B 000C 000D 000E 000F
0000 0000 0000 FE10 FACE CAFE ACED CEDE


1234 5678 9ABC DEF0 0000 0000 F00D 0000
0000 0000 EEEE 1111 EEEE 1111 0000 0000
B1B2 F1F5 0000 0000 0000 0000 0000 0000
```


Assembly Languages

Characteristics

- Not portable
  - Each assembly lang instruction maps to one machine lang instruction
- Simple
  - Each instruction does a simple task
- Not expressive
  - Poor (code functionality / code size) ratio
- **Human readable!!!**

```
        movl    $0, %r10d
loop:
        cmpl    $1, %r11d
        jle     endloop

        addl    $1, %r10d

        movl    %r11d, %eax
        andl    $1, %eax
        je      else

        movl    %r11d, %eax
        addl    %eax, %r11d
        addl    %eax, %r11d
        addl    $1, %r11d

        jmp     endif
else:
        sarl    $1, %r11d
endif:
        jmp     loop
endloop:
```


Why Learn Assembly Language?

Q: Why learn assembly language?

A: Knowing assembly language helps you:

- Write faster code
  - In assembly language
  - In a high-level language!
- Understand what's happening "under the hood"
  - Someone needs to develop future computer systems
  - Maybe that will be you!

Why Learn x86-64 Assembly Lang?

Why learn **x86-64** assembly language?

Pros

- X86-64 is popular
- CourseLab computers are x86-64 computers
  - Program natively on CourseLab instead of using an emulator

Cons

- X86-64 assembly language is **big**
  - Each instruction is simple, but…
  - There are **many** instructions
  - Instructions differ widely

x86-64 Assembly Lang Subset

We'll study a popular subset

- As defined by precept ***x86-64 Assembly Language*** document

We'll study programs define functions that:

- Do not use floating point values
- Have parameters that are integers or addresses (but not structures)
- Have return values that are integers or addresses (but not structures)
- Have no more than 6 parameters

Claim: a reasonable subset

Agenda

Language Levels

Architecture

Assembly Language: Defining Global Data

Assembly Language: Performing Arithmetic

John Von Neumann (1903-1957)

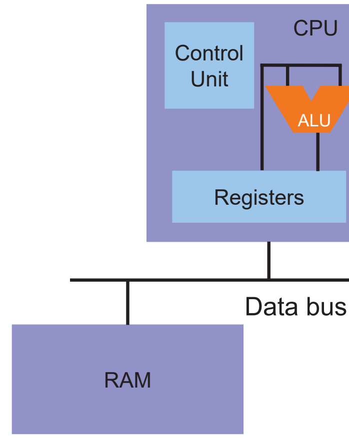
In computing
- Stored program computers
- Cellular automata
- Self-replication

Other interests
- Mathematics
- Inventor of game theory
- Nuclear physics (hydrogen bomb)

Princeton connection
- Princeton Univ & IAS, 1930-1957

Known for "Von Neumann architecture (1950)"
- In which programs are just data in the memory
- Contrast to the now-obsolete "Harvard architecture"

Von Neumann Architecture

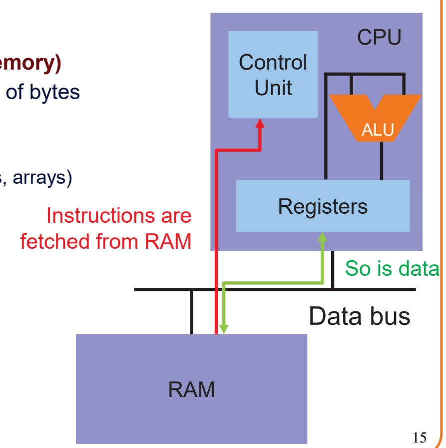


Von Neumann Architecture

RAM (Random Access Memory)

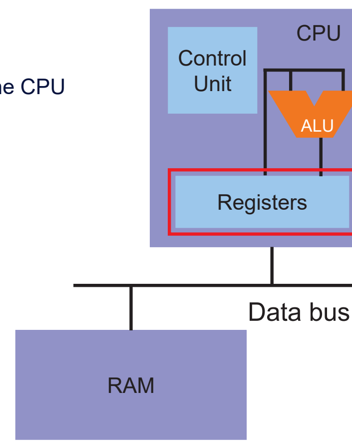
Conceptually: large array of bytes

- Contains data
  (program variables, structs, arrays)
- and the program!



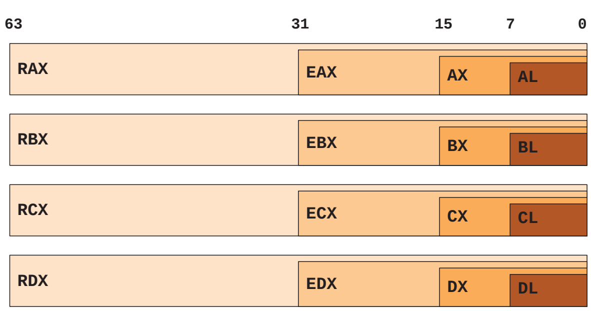
Von Neumann Architecture

Registers
- Small amount of storage on the CPU
- Much faster than RAM
- Top of the storage hierarchy
  - Above RAM, disk, …



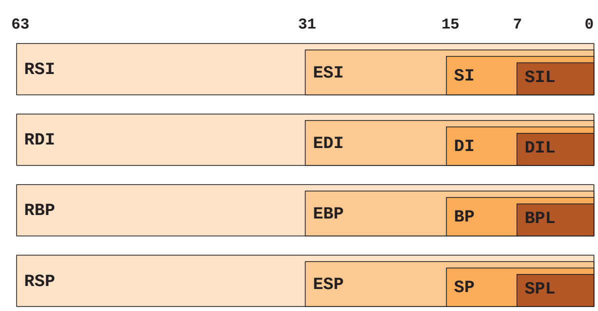
Registers (x86-64 architecture)

General purpose registers:



Registers (x86-64 architecture)

General purpose registers (cont.):



RSP is unique; see upcoming slide

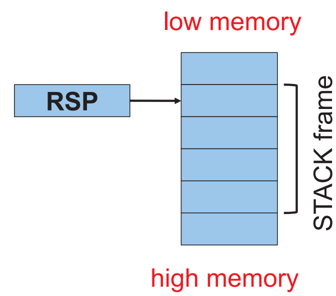
Registers (x86-64 architecture)

General purpose registers (cont.):

63	31	15	7 … 0
R8	R8D	R8W	R8B
R9	R9D	R9W	R9B
R10	R10D	R10W	R10B
R11	R11D	R11W	R11B
R12	R12D	R12W	R12B
R13	R13D	R13W	R13B
R14	R14D	R14W	R14B
R15	R15D	R15W	R15B

RSP Register

RSP (Stack Pointer) register
- Contains address of top (low address) of current function's stack frame



Allows use of the STACK section of memory, and special-purpose stack manipulation instructions

(See **Assembly Language: Function Calls** lecture)

EFLAGS Register

Special-purpose register…

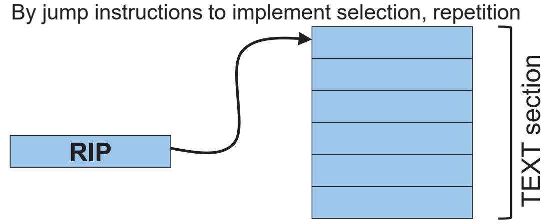
EFLAGS (Flags) register
- Contains **CC (Condition Code) bits**
- Affected by compare (`cmp`) instruction
  - And many others
- Used by conditional jump instructions
  - `je`, `jne`, `jl`, `jg`, `jle`, `jge`, `jb`, `jbe`, `ja`, `jae`, `...`

(See **Assembly Language: Part 2** lecture)

RIP Register

Special-purpose register…

RIP (Instruction Pointer) register
- Stores the location of the next instruction
  - Address (in TEXT section) of machine-language instructions to be executed next
- Value changed:
  - Automatically to implement sequential control flow
  - By jump instructions to implement selection, repetition



Registers summary

16 general-purpose 64-bit pointer/long-integer registers, many with stupid names:

rax, rbx, rcx, rdx, rsi, rdi, rbp, rsp, r8, r9, r10, r11, r12, r13, r14, r15

sometimes used as a "frame pointer" or "base pointer"

"stack pointer"

If you're operating on 32-bit "int" data, use these stupid names instead:

eax, ebx, ecx, edx, esi, edi, ebp, rsp, r8d, r9d, r10d, r11d, r12d, r13d, r14d, r15d

it doesn't really make sense to put 32-bit ints in the stack pointer

2 special-purpose registers: eflags rip

"condition codes" "program counter"

Registers and RAM

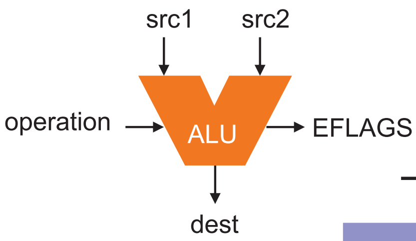
Typical pattern:
- **Load** data from RAM to registers
- **Manipulate** data in registers
- **Store** data from registers to RAM

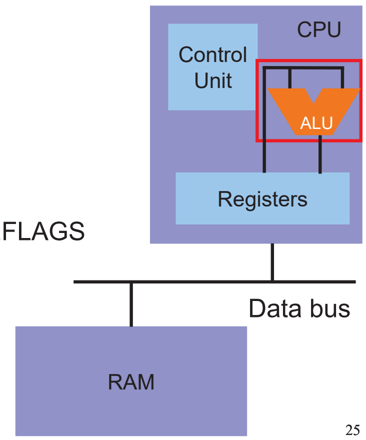
Many instructions combine steps

ALU

ALU (Arithmetic Logic Unit)

- Performs arithmetic and logic operations

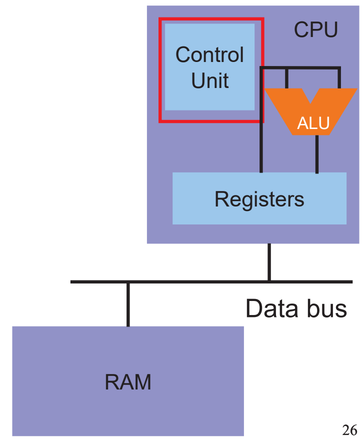




Control Unit

Control Unit

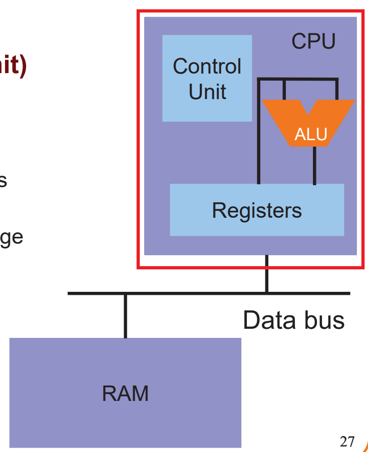
- Fetches and decodes each machine-language instruction
- Sends proper data to ALU



CPU

CPU (Central Processing Unit)

- Control unit
  - Fetch, decode, and execute
- ALU
  - Execute low-level operations
- Registers
  - High-speed temporary storage



Agenda

Language Levels

Architecture

Assembly Language: Defining Global Data

Assembly Language: Performing Arithmetic

Defining Data: DATA Section 1

```
static char c = 'a';
static short s = 12;
static int i = 345;
static long l = 6789;
```

```
   .section ".data"
c:
   .byte 'a'
s:
   .word 12
i:
   .long 345
l:
   .quad 6789
```

Note:

`.section` instruction (to announce DATA section)
label definition (marks a spot in RAM)
`.byte` instruction (1 byte)
`.word` instruction (2 bytes)
`.long` instruction (4 bytes)
`.quad` instruction (8 bytes)

Defining Data: DATA Section 2

```
char c = 'a';
short s = 12;
int i = 345;
long l = 6789;
```

```
    .section ".data"
    .globl c
c:  .byte 'a'
    .globl s
s:  .word 12
    .globl i
i:  .long 345
    .globl l
l:  .quad 6789
```

Note:

Can place label on same line as next instruction
`.globl` instruction

Defining Data: BSS Section

```
static char c;
static short s;
static int i;
static long l;
```

```
    .section ".bss"
c:
    .skip 1
s:
    .skip 2
i:
    .skip 4
l:
    .skip 8
```

Note:

`.section` instruction (to announce BSS section)

`.skip` instruction

Defining Data: RODATA Section

```
…
…"hello\n"…;
…
```

```
    .section ".rodata"
helloLabel:
    .string "hello\n"
```

Note:

`.section` instruction (to announce RODATA section)

`.string` instruction

Agenda

Language Levels

Architecture

Assembly Language: Defining Global Data

Assembly Language: Performing Arithmetic

Instruction Format

Many instructions have this format:

```
name{b,w,l,q} src, dest
```

- **name**: name of the instruction (**mov**, **add**, **sub**, **and**, etc.)

- **b**yte ⇒ operands are one-byte entities
- **w**ord ⇒ operands are two-byte entities
- **l**ong ⇒ operands are four-byte entities
- **q**uad ⇒ operands are eight-byte entitles

Instruction Format

Many instructions have this format:

```
name{b,w,l,q} src, dest
```

- **src: source operand**
  - The source of data
  - Can be
    - **Register operand**: **%rax**, **%ebx**, etc.
    - **Memory operand**: **5** (legal but silly), **someLabel**
    - **Immediate operand**: **$5**, **$someLabel**

Instruction Format

Many instructions have this format:

```
name{b,w,l,q} src, dest
```

- **dest: destination operand**
  - The destination of data
  - Can be
    - **Register operand**: **%rax**, **%ebx**, etc.
    - **Memory operand**: **5** (legal but silly), **someLabel**
  - Cannot be
    - **Immediate operand**

Performing Arithmetic: Long Data

```
static int length;
static int width;
static int perim;
…
perim =
  (length + width) * 2;
```

```
   .section ".bss"
length: .skip 4
width:  .skip 4
perim:  .skip 4
…
   .section ".text"
…
   movl length, %eax
   addl width, %eax
   sall $1, %eax
   movl %eax, perim
```

Note:
- `movl` instruction
- `addl` instruction
- `sall` instruction
- Register operand
- Immediate operand
- Memory operand
- `.section` instruction (to announce TEXT section)

Operands

Immediate operands
- **`$5`** ⇒ use the number 5 (i.e. the number that is available immediately within the instruction)
- **`$i`** ⇒ use the address denoted by i (i.e. the address that is available immediately within the instruction)
- Can be source operand; cannot be destination operand

Register operands
- **`%rax`** ⇒ read from (or write to) register RAX
- Can be source or destination operand

Memory operands
- **`5`** ⇒ load from (or store to) memory at address 5 (silly; seg fault)
- **`i`** ⇒ load from (or store to) memory at the address denoted by **`i`**
- Can be source or destination operand **(but not both)**
- There's more to memory operands; see next lecture

Performing Arithmetic: Byte Data

```
static char grade = 'B';
…
grade--;
```

```
   .section ".data"
grade: .byte 'B'
…
   .section ".text"
…
   # Option 1
   movb grade, %al
   subb $1, %al
   movb %al, grade
   …
   # Option 2
   subb $1, grade
   …
   # Option 3
   decb grade
```

Note:
- Comment
- `movb` instruction
- `subb` instruction
- `decb` instruction

iClicker Question

Q: What would happen if we used **`movl`** instead of **`movb`**?

A. Would always work correctly

B. Would always work incorrectly

C. Would sometimes work correctly

D. *This* code would work, but something else might go wrong that would cause you sleepless nights of painful debugging

```
   .section ".data"
grade: .byte 'B'
…
   .section ".text"
…
   # Option 1
   movb grade, %al
   subb $1, %al
   movb %al, grade
   …
   # Option 2
   subb $1, grade
   …
   # Option 3
   decb grade
```

iClicker Question

Q: What would happen if we used **`subl`** instead of **`subb`**?

A. Would always work correctly

B. Would always work incorrectly

C. Would sometimes work correctly

D. *This* code would work, but something else might go wrong that would cause you sleepless nights of painful debugging

```
   .section ".data"
grade: .byte 'B'
…
   .section ".text"
…
   # Option 1
   movb grade, %al
   subb $1, %al
   movb %al, grade
   …
   # Option 2
   subb $1, grade
   …
   # Option 3
   decb grade
```

More Arithmetic Instructions

```
add{q,l,w,b} srcIRM, destRM   dest += src
sub{q,l,w,b} srcIRM, destRM   dest -= src
inc{q,l,w,b} destRM           dest++
dec{q,l,w,b} destRM           dest--
neg{q,l,w,b} destRM           dest = -dest
```

Operand notation:
- src ⇒ source; dest ⇒ destination
- R ⇒ register; I ⇒ immediate; M ⇒ memory

Data Transfer Instructions

```
mov{q,l,w,b} srcIRM, destRM   dest = src
movsb{q,l,w} srcRM, destR     dest = src (sign extend)
movsw{q,l} srcRM, destR       dest = src (sign extend)
movslq srcRM, destR           dest = src (sign extend)
movzb{q,l,w} srcRM, destR     dest = src (zero fill)
movzw{q,l} srcRM, destR       dest = src (zero fill)
movzlq srcRM, destR           dest = src (zero fill)

cqto             reg[RDX:RAX] = reg[RAX] (sign extend)
cltd             reg[EDX:EAX] = reg[EAX] (sign extend)
cwtl             reg[EAX] = reg[AX] (sign extend)
cbtw             reg[AX] = reg[AL] (sign extend)
```


Multiplication and Division

Signed multiplication and division instructions

```
imulq srcRM              reg[RDX:RAX] = reg[RAX]*src
imull srcRM              reg[EDX:EAX] = reg[EAX]*src
imulw srcRM              reg[DX:AX] = reg[AX]*src
imulb srcRM              reg[AX] = reg[AL]*src
idivq srcRM              reg[RAX] = reg[RDX:RAX]/src
                         reg[RDX] = reg[RDX:RAX]%src
idivl srcRM              reg[EAX] = reg[EDX:EAX]/src
                         reg[EDX] = reg[EDX:EAX]%src
idivw srcRM              reg[AX] = reg[DX:AX]/src
                         reg[DX] = reg[DX:AX]%src
idivb srcRM              reg[AL] = reg[AX]/src
                         reg[AH] = reg[AX]%src
```

See Bryant & O'Hallaron book for description of signed vs. unsigned multiplication and division

Multiplication and Division

Unsigned multiplication and division instructions

```
mulq srcRM               reg[RDX:RAX] = reg[RAX]*src
mull srcRM               reg[EDX:EAX] = reg[EAX]*src
mulw srcRM               reg[DX:AX] = reg[AX]*src
mulb srcRM               reg[AX] = reg[AL]*src
divq srcRM               reg[RAX] = reg[RDX:RAX]/src
                         reg[RDX] = reg[RDX:RAX]%src
divl srcRM               reg[EAX] = reg[EDX:EAX]/src
                         reg[EDX] = reg[EDX:EAX]%src
divw srcRM               reg[AX] = reg[DX:AX]/src
                         reg[DX] = reg[DX:AX]%src
divb srcRM               reg[AL] = reg[AX]/src
                         reg[AH] = reg[AX]%src
```

See Bryant & O'Hallaron book for description of signed vs. unsigned multiplication and division

Bit Manipulation

Bitwise instructions

```
and{q,l,w,b} srcIRM, destRM    dest = src & dest
or{q,l,w,b}  srcIRM, destRM    dest = src | dest
xor{q,l,w,b} srcIRM, destRM    dest = src ^ dest
not{q,l,w,b} destRM            dest = ~dest
sal{q,l,w,b} srcIR, destRM     dest = dest << src
sar{q,l,w,b} srcIR, destRM     dest = dest >> src (sign extend)
shl{q,l,w,b} srcIR, destRM     (Same as sal)
shr{q,l,w,b} srcIR, destRM     dest = dest >> src (zero fill)
```


Summary

Language levels

The basics of computer architecture
- Enough to understand x86-64 assembly language

The basics of x86-64 assembly language
- Instructions to define global data
- Instructions to perform data transfer and arithmetic

To learn more
- Study more assembly language examples
  - Chapter 3 of Bryant and O'Hallaron book
- Study compiler-generated assembly language code
  - **gcc217 -S somefile.c**

Appendix

Big-endian vs little-endian byte order

Byte Order

x86-64 is a **little endian** architecture

- **Least** significant byte of multi-byte entity is stored at lowest memory address
- "Little end goes first"

The int 5 at address 1000:

1000	00000101
1001	00000000
1002	00000000
1003	00000000

Some other systems use **big endian**

- **Most** significant byte of multi-byte entity is stored at lowest memory address
- "Big end goes first"

The int 5 at address 1000:

1000	00000000
1001	00000000
1002	00000000
1003	00000101

Byte Order Example 1

```
#include <stdio.h>
int main(void)
{  unsigned int i = 0x003377ff;
   unsigned char *p;
   int j;
   p = (unsigned char *)&i;
   for (j=0; j<4; j++)
      printf("Byte %d: %2x\n", j, p[j]);
}
```

Output on a little-endian machine

```
Byte 0: ff
Byte 1: 77
Byte 2: 33
Byte 3: 00
```

Output on a big-endian machine

```
Byte 0: 00
Byte 1: 33
Byte 2: 77
Byte 3: ff
```


Byte Order Example 2

Note:

Flawed code; uses "b" instructions to manipulate a four-byte memory area

```
   .section ".data"
grade: .long 'B'
…
   .section ".text"
   …
   # Option 1
   movb grade, %al
   subb $1, %al
   movb %al, grade
   …
   # Option 2
   subb $1, grade
```

x86-64 is **little** endian, so what will be the value of grade?

What would be the value of grade if x86-64 were **big** endian?

Byte Order Example 3

Note:

Flawed code; uses "l" instructions to manipulate a one-byte memory area

```
   .section ".data"
grade: .byte 'B'
…
   .section ".text"
…
   # Option 1
   movl grade, %eax
   subl $1, %eax
   movl %eax, grade
   …
   # Option 2
   subl $1, grade
```

What would happen?