Assembly Language: Overview

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Second Half of the Course

- Toward the hardware
  - Computer architecture
  - Assembly language
  - Machine language
- Toward the operating system
  - Virtual memory
  - Dynamic memory management
  - Processes and pipes
  - Signals and system calls

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Goals of Today's Lecture

- Help you learn…
  - Basics of computer architecture
  - Relationship between C and assembly language
  - IA-32 assembly language through an example
- Why?
  - Write faster code in high-level languages
  - Understand how the underlying hardware works
  - Know how to write assembly code when needed

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Three Levels of Languages

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High-Level Language

- Make programming easier by describing operations in a semi-natural language
- Increase the portability of the code
- One line may involve many low-level operations
- Examples: C, C++, Java, Pascal, …

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

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Assembly Language

- Tied to the specifics of the underlying machine
- Commands and names to make the code readable and writeable by humans
- Hand-coded assembly code may be more efficient
- E.g., IA-32 from Intel

```
        movl    $0, %ecx
loop:
        cmpl    $1, %edx
        jle     endloop
        addl    $1, %ecx
        movl    %edx, %eax
        andl    $1, %eax
        je      else
        movl    %edx, %eax
        addl    %eax, %edx
        addl    %eax, %edx
        addl    $1, %edx
        jmp     endif
else:
        sarl    $1, %edx
endif:
        jmp     loop
endloop:
```

Machine Language

- Also tied to the underlying machine
- What the computer sees and deals with
- Every instruction is a sequence of one or more numbers
- All stored in memory on the computer, and read and executed
- Unreadable by humans

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

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Why Learn Assembly Language?

- Write faster code (even in high-level language)
  - By understanding which high-level constructs are better
  - … in terms of how efficient they are at the machine level
- Understand how things work underneath
  - Learn the basic organization of the underlying machine
  - Learn how the computer actually runs a program
  - Design better computers in the future
- Some software is still written in assembly language
  - Code that really needs to run quickly
  - Code for embedded systems, network processors, etc.

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Why Learn Intel IA-32 Assembly?

- Program natively on our computing platform
  - Rather than using an emulator to mimic another machine
- Learn instruction set for the most popular platform
  - Most likely to work with Intel platforms in the future
- But, this comes at some cost in complexity
  - IA-32 has a large and varied set of instructions
  - More instructions than are really useful in practice
- Fortunately, you won't need to use everything

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Computer Architecture

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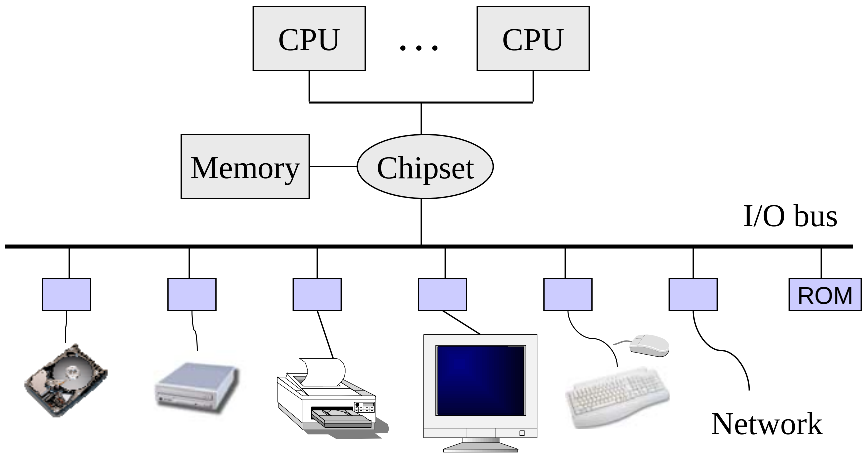
A Typical Computer



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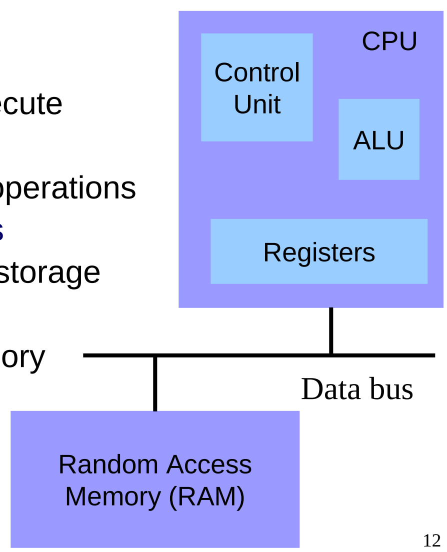
Von Neumann Architecture

- Central Processing Unit
  - Control unit
    - Fetch, decode, and execute
  - Arithmetic and logic unit
    - Execution of low-level operations
  - General-purpose registers
    - High-speed temporary storage
  - Data bus
    - Provide access to memory



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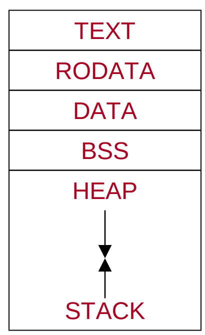
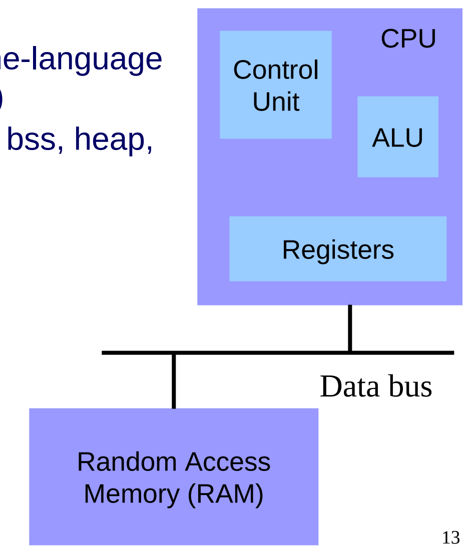
Von Neumann Architecture

- Memory
  - Store executable machine-language instructions (text section)
  - Store data (rodata, data, bss, heap, and stack sections)





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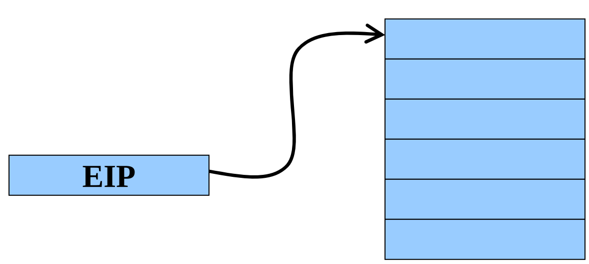
Control Unit: Instruction Pointer

- Stores the location of the next instruction
  - Address to use when reading machine-language instructions from memory (i.e., in the text section)
- Changing the instruction pointer (EIP)
  - Increment to go to the next instruction
  - Or, load a new value to “jump” to a new location



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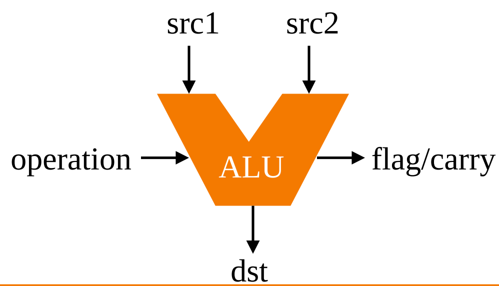
Control Unit: Instruction Decoder

- Determines what operations need to take place
  - Translate the machine-language instruction
- Control what operations are done on what data
  - E.g., control what data are fed to the ALU
  - E.g., enable the ALU to do multiplication or addition
  - E.g., read from a particular address in memory

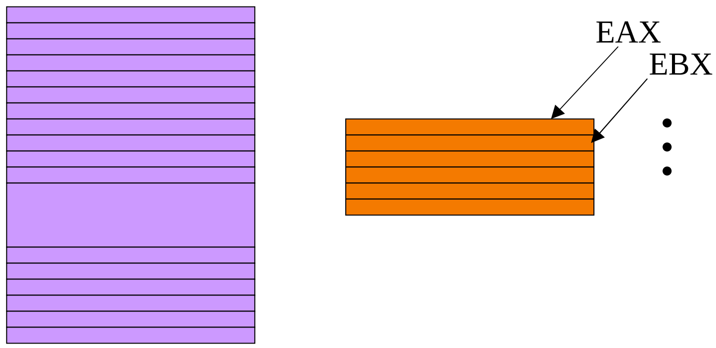


Registers

- Small amount of storage on the CPU
  - Can be accessed more quickly than main memory
- Instructions move data in and out of registers
  - Loading registers from main memory
  - Storing registers to main memory
- Instructions manipulate the register contents
  - Registers essentially act as temporary variables
  - For efficient manipulation of the data
- Registers are the top of the memory hierarchy
  - Ahead of main memory, disk, tape, …

Keeping it Simple: All 32-bit Words

- Simplifying assumption: all data in four-byte units
  - Memory is 32 bits wide
  - Registers are 32 bits wide



- In practice, can manipulate different sizes of data

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C Code vs. Assembly Code

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Kinds of Instructions

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

- Reading and writing data
  - count = 0
  - n
- Arithmetic and logic operations
  - Increment: count++
  - Multiply: n * 3
  - Divide: n/2
  - Logical AND: n & 1
- Checking results of comparisons
  - Is (n > 1) true or false?
  - Is (n & 1) non-zero or zero?
- Changing the flow of control
  - To the end of the while loop (if “n > 1”)
  - Back to the beginning of the loop
  - To the else clause (if “n & 1” is 0)

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Variables in Registers

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

<u>Registers</u>

```
n      %edx
count  %ecx
```

Referring to a register: percent sign (“%”)

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Immediate and Register Addressing

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

```
movl   $0, %ecx
addl   $1, %ecx
```

Read directly from the instruction

written to a register

Referring to a immediate operand: dollar sign ("$")

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Immediate and Register Addressing

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

```
movl   %edx, %eax
andl   $1, %eax
```

Computing intermediate value in register EAX

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Immediate and Register Addressing

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

```
movl  %edx, %eax
addl  %eax, %edx
addl  %eax, %edx
addl  $1, %edx
```

Adding n twice is cheaper than multiplication!

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Immediate and Register Addressing

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

```
sarl  $1, %edx
```

Shifting right by 1 bit is cheaper than division!

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Changing Program Flow

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

- Cannot simply run next instruction
  - Check result of a previous operation
  - Jump to appropriate next instruction
- Flags register (EFLAGS)
  - Stores the status of operations, such as comparisons, as a side effect
  - E.g., last result was positive, negative, zero, etc.
- Jump instructions
  - Load new address in instruction pointer
- Example jump instructions
  - Jump unconditionally (e.g., "}")
  - Jump if zero (e.g., "n&1")
  - Jump if greater/less (e.g., "n>1")

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Conditional and Unconditional Jumps

- Comparison **`cmpl`** compares two integers
  - Done by subtracting the first number from the second
    - Discarding the results, but setting flags as a side effect
  - Example:
    - **`cmpl $1, %edx`** (computes %edx – 1)
    - **`jle endloop`** (checks whether result was 0 or negative)
- Logical operation **`andl`** compares two integers
  - Example:
    - **`andl $1, %eax`** (bit-wise AND of %eax with 1)
    - **`je else`** (checks whether result was 0)
- Also, can do an unconditional branch **`jmp`**
  - Example:
    - **`jmp endif`** and **`jmp loop`**

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Jump and Labels: While Loop

```
while (n>1) {

}
```

```
loop:
        cmpl   $1, %edx
        jle    endloop
        …

        jmp    loop
endloop:
```

Checking if EDX is less than or equal to 1.

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Jump and Labels: While Loop

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

```
        movl   $0, %ecx
loop:
        cmpl   $1, %edx
        jle    endloop
        addl   $1, %ecx
        movl   %edx, %eax
        andl   $1, %eax
        je     else
        movl   %edx, %eax
        addl   %eax, %edx
        addl   %eax, %edx
        addl   $1, %edx
        jmp    endif
else:
        sarl   $1, %edx
endif:
        jmp    loop
endloop:
```

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Jump and Labels: If-Then-Else

```
if (n&1)
  ...
else
  ...
```

```
            movl  %edx, %eax
            andl  $1, %eax
            je    else
            …
            jmp   endif
    else:
            …
    endif:
```

"then" block

"else" block

Jump and Labels: If-Then-Else

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

```
            movl  $0, %ecx
    loop:
            cmpl  $1, %edx
            jle   endloop
            addl  $1, %ecx
            movl  %edx, %eax
            andl  $1, %eax
            je    else
            movl  %edx, %eax
            addl  %eax, %edx
            addl  %eax, %edx
            addl  $1, %edx
            jmp   endif
    else:
            sarl  $1, %edx
    endif:
            jmp   loop
    endloop:
```

"then" block

"else" block

Making the Code More Efficient…

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

```
        movl  $0, %ecx
loop:
        cmpl  $1, %edx
        jle   endloop
        addl  $1, %ecx
        movl  %edx, %eax
        andl  $1, %eax
        je    else
        movl  %edx, %eax
        addl  %eax, %edx
        addl  %eax, %edx
        addl  $1, %edx
        jmp   endif
else:
        sarl  $1, %edx
endif:
        jmp   loop
endloop:
```

Replace with "jmp loop"

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Complete Example

n %edx
count %ecx

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

```
        movl  $0, %ecx
loop:
        cmpl  $1, %edx
        jle   endloop
        addl  $1, %ecx
        movl  %edx, %eax
        andl  $1, %eax
        je    else
        movl  %edx, %eax
        addl  %eax, %edx
        addl  %eax, %edx
        addl  $1, %edx
        jmp   endif
else:
        sarl  $1, %edx
endif:
        jmp   loop
endloop:
```

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Reading IA-32 Assembly Language

- Referring to a register: percent sign (“%”)
  - E.g., “%ecx” or “%eip”
- Referring to immediate operand: dollar sign (“$”)
  - E.g., “$1” for the number 1
- Storing result: typically in the second argument
  - E.g. “addl $1, %ecx” increments register ECX
  - E.g., “movl %edx, %eax” moves EDX to EAX
- Assembler directives: starting with a period (“.”)
  - E.g., “.section .text” to start the text section of memory
- Comment: pound sign (“#”)
  - E.g., “# Purpose: Convert lower to upper case”

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Conclusions

- Assembly language
  - In between high-level language and machine code
  - Programming the “bare metal” of the hardware
  - Loading and storing data, arithmetic and logic operations, checking results, and changing control flow
- To get more familiar with IA-32 assembly
  - Read more assembly-language examples
    - Chapter 3 of Bryant and O’Hallaron book
  - Generate your own assembly-language code
    - gcc217 –S –O2 code.c

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