CSCI 210: Computer Organization
Lecture 2: Assembly Language

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Slides from Cynthia Taylor

Announcements

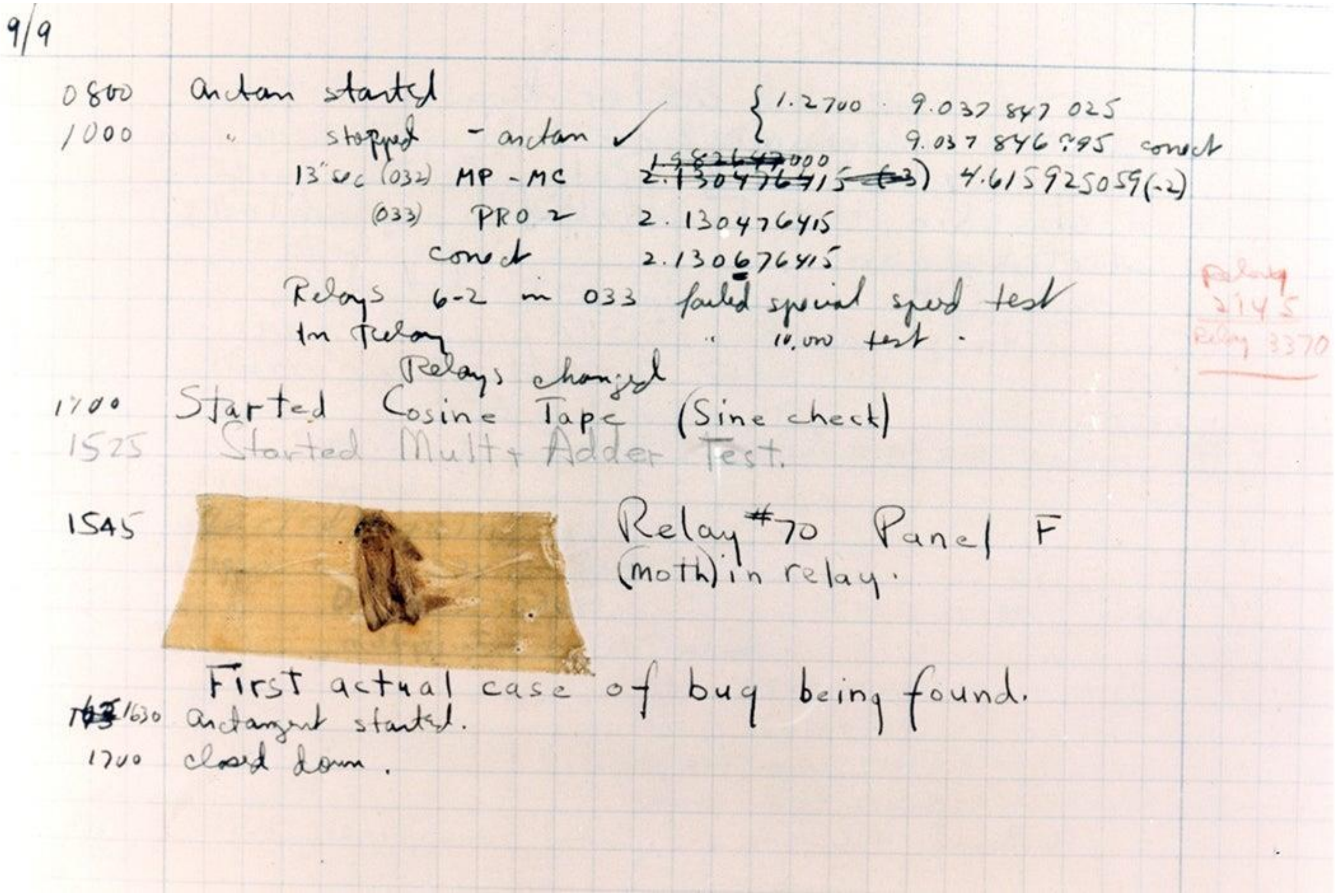
- Reading due before class, linked from blackboard

- Problem set 0 due Friday at 23:59
  - On GradeScope, linked from blackboard

CS History: Rear Admiral Grace Hopper

- Invented the compiler
- Conceptualized machine-independent programming languages.
- Popularized term “debugging”

Not actually the first use of “bug” but a good story nevertheless



https://daily.jstor.org/the-bug-in-the-computer-bug-story/

How to Speak Computer?

10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100

2

lw $15, 0($2)
lw $16, 4($2)
sw $16, 0($2)
sw $15, 4($2)

1

temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;

3

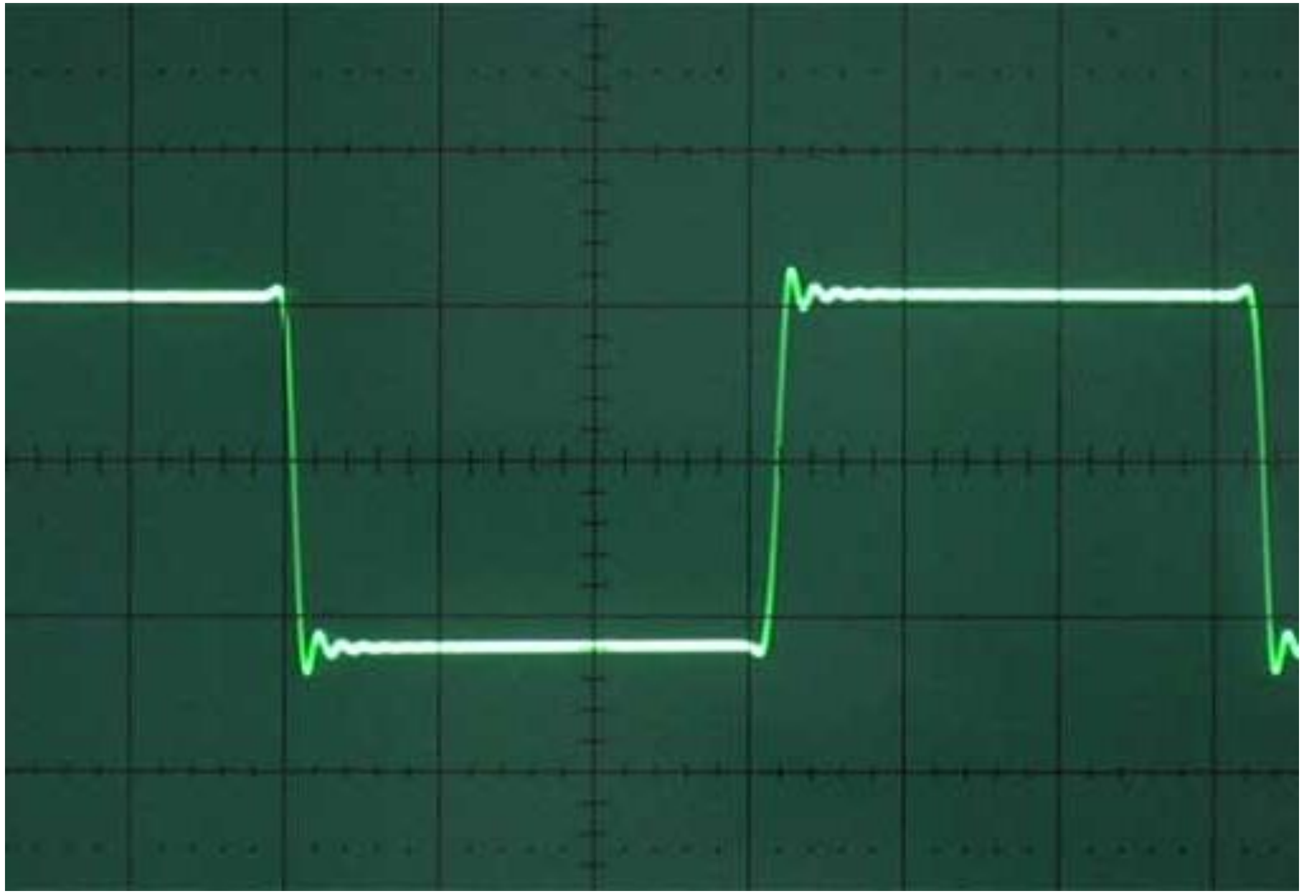
Selection	High Level Language	Assembly	Machine Language
A	3	2	1
B	3	1	2
C	2	1	2
D	1	2	2
E	None of the above		

What Your CPU Understands

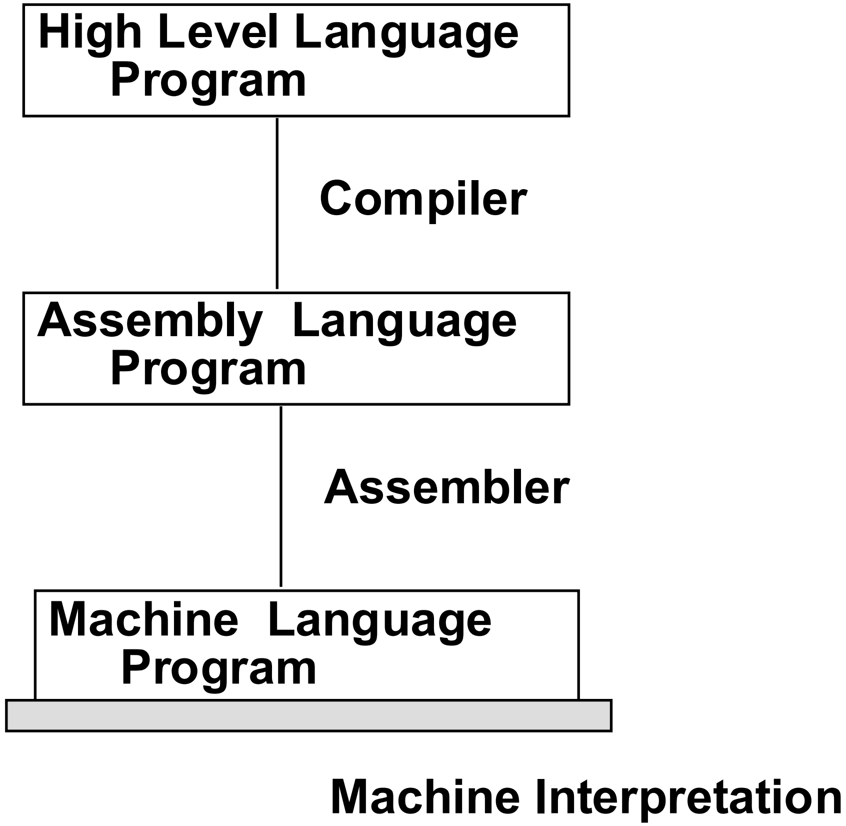
Electricity

Ones and zeros

Problem: People don’t like writing programs in ones and zeros

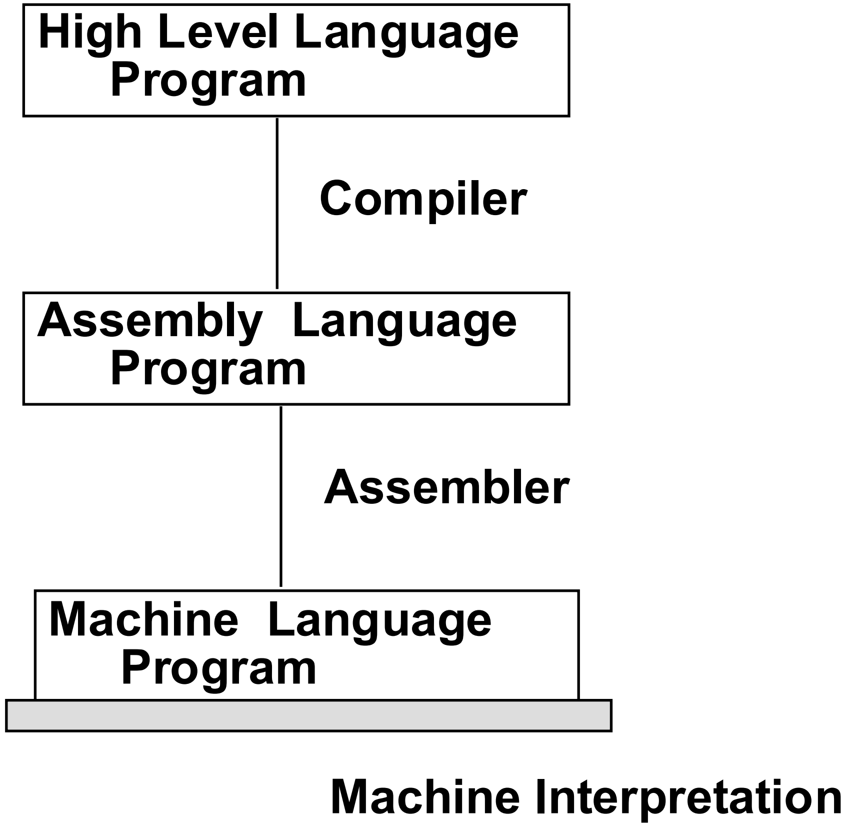


How to Speak Computer




```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

How to Speak Computer




```
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v[k] = v[k+1];
v[k+1] = temp;
```
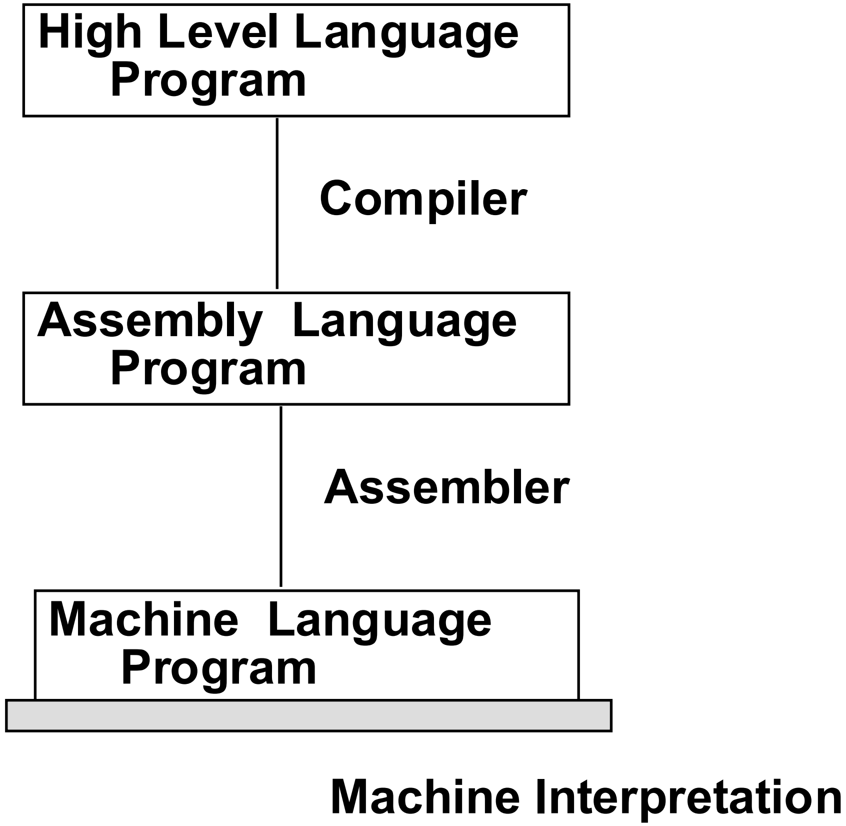

```
lw  $15,   0($2)
lw  $16,   4($2)
sw  $16,   0($2)
sw  $15,   4($2)
```

How to Speak Computer



temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;

```
lw  $15,  0($2)
lw  $16,  4($2)
sw  $16,  0($2)
sw  $15,  4($2)
```

10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100

How to Speak Computer

High Level Language Program

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

Compiler

Assembly Language Program

```
lw  $15,    0($2)
lw  $16,    4($2)
sw  $16,    0($2)
sw  $15,    4($2)
```

Assembler

Machine Language Program

```
10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100
```

Machine Interpretation

Machine does something!

Let’s look at these in reverse order

- Starting with “machine does something”
- Build up to high-level languages
- At each step, we’re building **abstractions** that the next higher-level can use

- WARNING: Everything I’m about to say is mostly correct but definitely not complete!

Machine does something

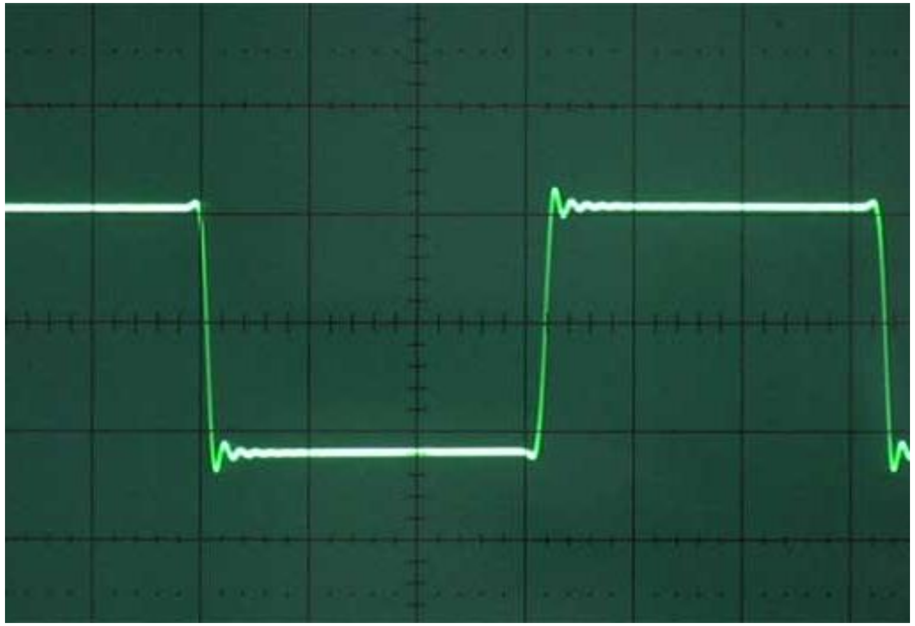
- At the lowest level (that we’ll talk about) we have **transistors** which act (sort of) like electrical switches
- These transistors are organized into groups and connected together to perform operations like “add numbers—which are represented by a sequence of electrical voltages—together”
- A modern processor—a CPU—is built from billions of transistors

Central Processing Unit (CPU)

- The CPU operates by processing a stream of machine-language instructions which, **exactly like** numbers, are represented by a sequence of electrical voltages
- The instructions dictate which operation (like addition or multiplication) to perform and what data to perform it on
- The CPU contains a **very** small amount of memory called **registers** (built out of transistors!) to store the data it operates on
  - How small? It holds about 30 numbers.

Correspondence between instructions/numbers and sequences of voltages

- The CPU works with voltages but humans work with numbers and instructions
- We represent numbers/instructions as sequences of 0s and 1s
- These correspond to voltages:
  - 0 corresponds to a voltage < .5 V
  - 1 corresponds to a voltage > .5 V



Registers

- (Very) Small amount of memory inside the CPU
- Data is put into a register before it is used by an instruction
- Manipulated data is then stored back in main memory (RAM).

Aside: Multi-core CPUs

- Modern CPUs contains one or more “cores,” each of which executes instructions independently from the other cores (we’re going to only focus on single-core CPUs but the same ideas apply to multi-core CPUs)

Machine Language

Machine Language Program

10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100

- Abstracts from voltage levels to 0s and 1s
- A machine language program tells the CPU what to do
- It consists of a sequence of individual instructions
- Each instruction is a sequence of 0s and 1s
  - In this class, each instruction is a sequence of exactly 32 0s and 1s

Typical Machine Language Operations (with corresponding machine language instruction)

- Load data from main memory (RAM) into a register
  - 1000 1110 0000 1000 0000 0000 0000 0000
- Store the contents of a register into main memory
  - 1010 1110 0100 1010 0000 0000 0000 0000
- Compute the sum (or difference) of two registers, store the result in a register
  - 0000 0001 0010 1010 0100 0000 0010 0000
- Change which instruction runs next (e.g., for a loop)
  - 0000 1000 0001 0000 0000 0000 0000 0111
- Change which instruction runs next based on a register value (e.g., for if)
  - 0001 0001 0000 1001 1111 1111 1111 1111

Machine-language is the lowest level abstraction programmer can use to program a particular machine

- We used to toggle physical switches to load machine-language into the computer

- This is painful!

Instruction Set Architecture (ISA)

- The definition (specification) of a machine language supported by a CPU
- Encompasses all the information necessary to write a machine language program, including instructions, registers, memory access, …
- Usually defines a human-readable assembly language which has a 1-1 correspondence with machine-language
  - No more writing code in 0s and 1s!

Examples of ISAs

- Intel x86, x86_64
- **MIPS32**, MIPS64
- ARM: A32 (32-bit ARM), A64 (64-bit ARM), T32 (Thumb), Apple Silicon
- Power ISA (PowerPC)
- Risc-V

Which of the following statement is generally true about ISAs?

Select	Statement
A	Some models of processors support exactly one ISA, others support multiple (usually related) ISAs
B	An ISA is unique to one model of processor.
C	Every processor supports multiple ISAs.
D	Each processor manufacturer has its own unique ISA.
E	None of the above

How to Speak Computer

High Level Language Program

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

Compiler

Assembly Language Program

```
lw  $15,   0($2)
lw  $16,   4($2)
sw  $16,   0($2)
sw  $15,   4($2)
```

Assembler

Machine Language Program

```
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10101100011000100000000000000100
```

Machine Interpretation

Machine does something!

Assembly Language

- Abstraction of machine language
  - From 1s & 0s to symbolic names
- Allows direct access to architectural features (registers, memory)
- Symbolic names are used for
  - operations (mnemonics)
  - memory locations (variables, branch labels)
- There's usually a single assembly language corresponding to a machine language
  - x86 has at least 2 distinct assembly languages (Intel and AT&T) with multiple variants of each; x86 is *weird* in a bunch of respects

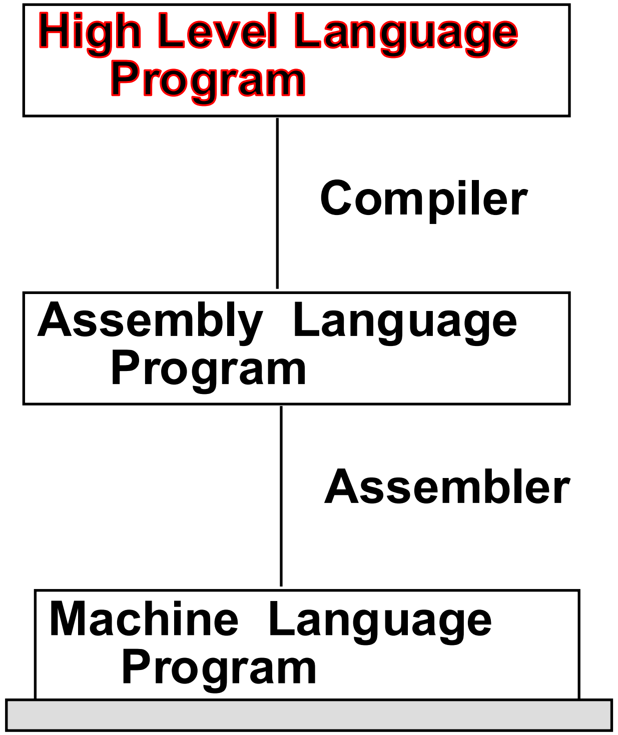
Assembler

- A program called an **assembler** converts assembly-language programs to their equivalent machine-language programs
- The input is a text file containing an assembly program
- The output is a binary file containing a machine language program

Aside

- Sometimes CPUs support undocumented or even unintended instructions
- These instructions often don’t have an official symbolic name and so have to be written in machine language
- Such instructions were common in old CPUs which didn’t check for illegal instructions
- Modern CPUs will (usually) detect an illegal instruction and prevent the program from continuing

How to Speak Computer



Machine Interpretation

```
temp = v[k];
v[k] = v[k+1];
v[k+1] = temp;
```

```
lw  $15,   0($2)
lw  $16,   4($2)
sw  $16,   0($2)
sw  $15,   4($2)
```

```
10001100011000100000000000000000
10001100111100100000000000000100
10101100111100100000000000000000
10101100011000100000000000000100
```

Machine does something!

High-level code

```
x = 4;
y = 5;
x = x + y;
```

MIPS code

```
addi $t0, $zero, 4   #set $t0 to 4
addi $t1, $zero, 5   #set $t1 to 5
add $t0, $t0, $t1    #perform the add
```

Usually, 1 line of high-level code is translated to multiple assembly instructions; these are very simple

Compiler

- A program called a **compiler** translates high-level code like C or Rust into assembly language
- The input is a text file containing a high-level program
- The output is a text file containing an assembly program

- Some compilers (like clang or rustc) incorporate an assembler and go directly from high-level programs to machine language programs; others (like gcc) run the assembler as a separate program

Abstractions recap

- Transistors operating via electricity
- Abstraction: machine-language specifying operations in 0s and 1s
- Abstraction: assembly-language specifying operations in human-readable text
- Abstraction: high-level language specifying algorithms

Group Discussion: What are some advantages to a high-level language over programming in assembly?

A single program written in a high-level language can be compiled into _______ assembly language programs

A. Exactly one

B. Multiple

C. At most three

A single program written in assembly can be assembled into _______ machine language programs

A. Exactly one

B. Multiple

C. At most two

High-level language program (in C)

```
void swap (int v[], int k) {
    int temp;
    temp = v[k];
    v[k] = v[k+1];
    v[k+1] = temp;
}
```

C compiler

one-to-many

Assembly language program (for MIPS)

```
swap:  sll $2, $5, 2
    add $2, $4, $2
    lw  $15, 0($2)
    lw  $16, 4($2)
    sw  $16, 0($2)
    sw  $15, 4($2)
    jr  $31
```

assembler

one-to-one

Machine (object, binary) code (for MIPS)

```
000000 00000 00101 0001000010000000
000000 00100 00010 0001000000100000
 . . .
```

Reading

- Next lecture: Hardware!
  - Sections 1.4 and 1.5

- Problem set 0 due Friday at 11:59 p.m.