COMP 102: Excursions in Computer Science
Lecture 7: Interpreting the program

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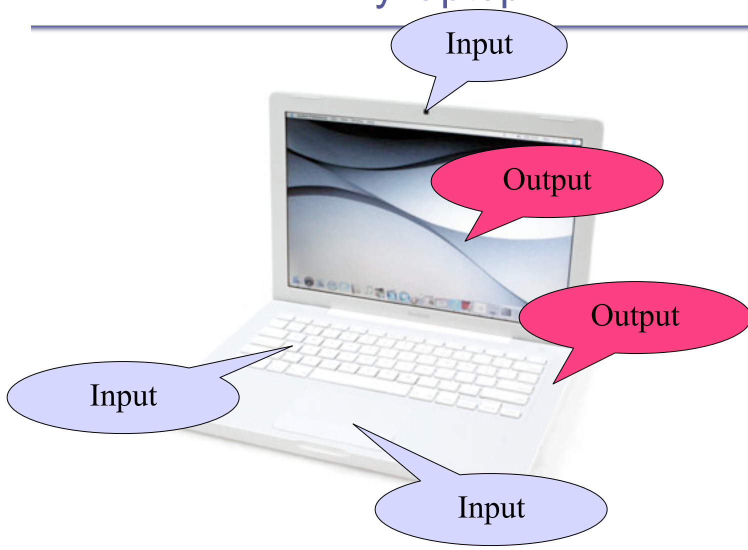
Quick Recap

- Weeks 1-2: Hardware approach
  - Every problem is expressed with boolean variables and operators.
  - Can implement any function using the right combination of AND, OR, NOT.
  - Hardware solutions are quick (in terms of machine running time.)
  - But this is very inflexible (need a new circuit for each program!)
- Week 3: Software approach
  - Always same hardware, same set of circuits (any standard computer)
  - Can implement a large variety of programs and be reprogrammed.
  - Need a layer to translate the programming language into something the computer will understand.

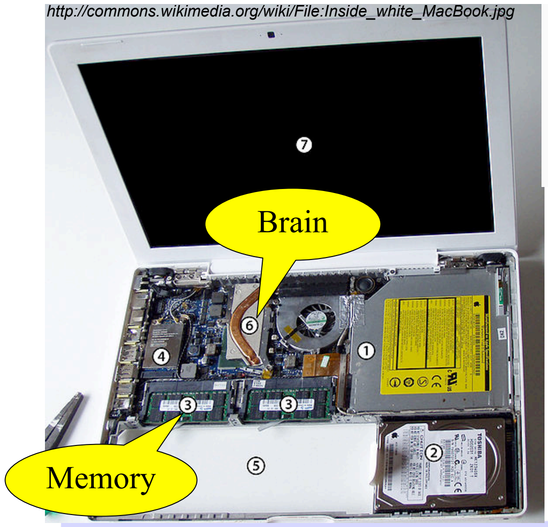
Today's lecture: Machine Language

My laptop



Inside the laptop

http://commons.wikimedia.org/wiki/File:Inside_white_MacBook.jpg

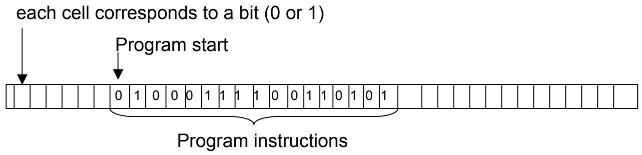


1. : Optical Driver
2. : Hard Disk
3. : RAM
4. : Aiport Extreme card
5. : Battery
6. : Processor & chipset covered by heat pipe
7. : 13.3" Screen

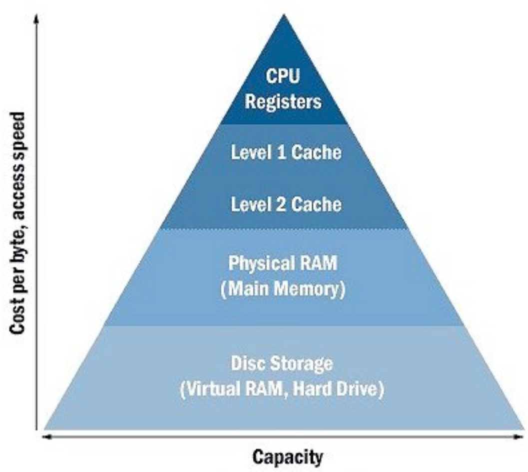
- MagSafe power port
- Gigabit Ethernet port
- Mini DisplayPort
- Two USB 2.0 ports (up to 480 Mbps)
- Audio in/out
- Kensington lock slot

Simplifying the picture

- CPU: Performs the operations in the current instruction.
- Memory: Stores the program (sequence of instructions and data).
  RAM = Random Access Memory

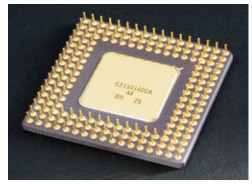


Forms of memory



http://www.real-knowledge.com/memory.htm

CPU: Central Processing Unit



The CPU is composed of 3 major parts:

- ALU (Arithmetic Logic Unit)
  - Arithmetic & Logical operations
- Registers
  - Storage areas for data and machine instructions operated on by ALU
- Control unit
  - Acts as a coordinator between the ALU and registers

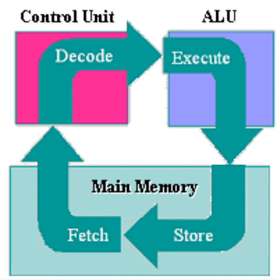
Instructions do very **simple** things

- Read bits (i.e. accessing variables).
- Change the bits in a location (i.e. assigning variables).
- Move bits from 1 cell to another.
- Treat some bits as numbers to apply arithmetic operations (add, subtract, multiply, …)
- Modify which instruction is executed next -> CONTROL FLOW
- Communicate with external devices.

Fetch-Decode-Execute Cycle

1. Fetch Cycle: The Control Unit *fetches* the next instruction from memory.
2. Decode Cycle: The Control Unit *decodes* the instruction (figuring out what the bits represent).
3. Execute Cycle: The ALU *executes* the required instruction and stores results into memory.

This is the <u>only</u> thing the CPU does!



Fetch-Decode

1. Look at the Program Counter (PC) to determine the location in memory where the next instruction is stored
2. Retrieve this instruction from program memory
3. Decode this instruction
4. After an instruction is fetched, increment the PC by the length of the instruction

Length of instructions

- Most computer architectures assume all instructions are 32-bit long. Easy to know how many bits to *fetch* at a time!

- More recently, new architectures use 64-bit instructions.
  - Twice as much information per cycle = faster computing!

Problem!

Problem #1: Need to convert the program into a long stream of bits.

- Some parts are actual memory (e.g. variables).
- Some parts are the instructions / operations.

- Writing a program as bits directly is tedious!
- There are human-readable mnemonics for bit patterns.

Machine Instructions

MIPS32 Add Immediate Instruction

001000	00001	00010	0000000101011110
OP Code	Addr 1	Addr 2	Immediate value

Equivalent mnemonic: **addi $r1 , $r2 , 350**

English translation:

Add the contents of the *register* r2 and 350 and store the result in the *register* r1

Machine Instructions

- Other kinds of instructions include:
  - Transferring data between registers or memory locations
  - Arithmetic or logical operations (use the ALU)
  - Control: test contents of a register and jump to a location

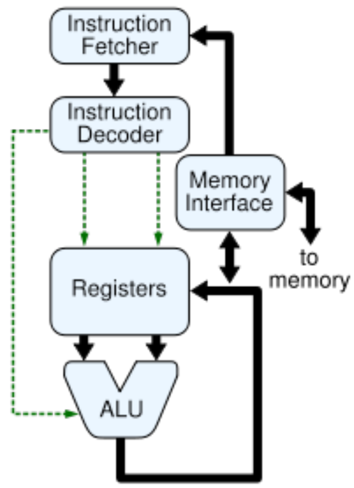
- There are binary codes for each of these (and associated mnemonics).

  E.g. *http://www.mrc.uidaho.edu/mrc/people/jff/digital/MIPSir.html*

Execute Cycle

1. Execute the instruction
   – Connects the various components of the computer so that the desired operation may be carried out.

2. Write back the results (if any) of the execute step to some form of memory.



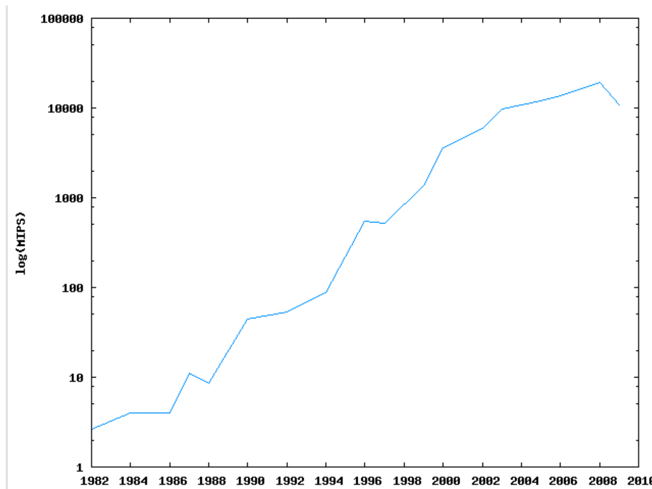
Computer Speed

- The CPU experiences high and low voltage changes, driven by the internal **clock** (vibrating quartz crystal).
  – The clock operates with a predetermined **frequency** (such as 2.4GHz).

- Each time the clock changes, the computer's processor handles the next machine instruction.

- A more accurate measurement would compare the **number of instructions per second** (MIPS: million instructions per second) as some computers use the clock ticks more efficiently than others.
  – Apple’s MacBook (2009) handles ~10,000 MIPS.

MIPS increasing



http://modelingwithdata.org/arch/00000002.htm

Example of an Executable

```
00100111101111011111111111100000
10101111101111110000000000010100
10101111101001000000000000100000
10101111101001010000000000100100
10101111101000000000000000011000
10101111101000000000000000011100
10001111101011100000000000011100
10001111101110000000000000011000
00000001110011100000000000011001
00100101110010000000000000000001
00101001000000010000000001100101
10101111101010000000000000011100
00000000000000000111100000010010
00000011000011111100100000100001
00010100001000001111111111110111
10101111101110010000000000011000
00111100000001000001000000000000
10001111101001010000000000011000
00001100000100000000000011101100
00100100100001000000010000110000
10001111101111110000000000010100
00100111101111010000000000100000
00000011111000000000000000001000
00000000000000000001000000100001
```

FIGURE A.1.2 MIPS machine language code for a routine to compute and print the sum of the squares of integers between 0 and 100.

http://pages.cs.wisc.edu/~larus/HP_AppA.pdf

Back to programming languages

- We write programs in a user-friendly programming language:

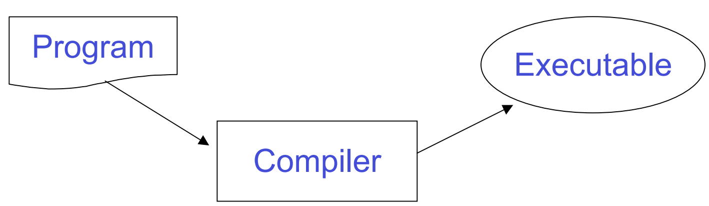
```
Integer sum
Integer x
sum = 0
For x = 1 to 100
        sum = sum + x*x
End loop
Print sum
```

- How can we convert:

High-level programming language ←→ Low-level machine language

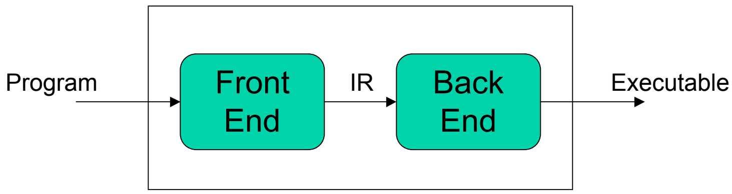
- This is a job for a **compiler**.

Compiler



- The compiler translates high-level programming language into low-level machine language: **Program** -> **Executable**
  - Each programming language needs its own compiler.
- Note: The compiler is a program! (So need a compiler for the compiler…)
  - Here's an idea: Our compiler is actually compiled by itself!

Compiler

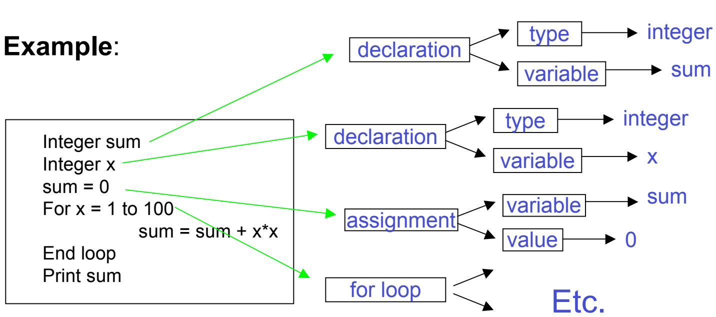


- **Front End**: Needs to know all about the input language.
- **Back End**: Knows all about the machine itself (CPU).
- Intermediate representation (IR):
  - Generated by the Front End, understood by the Back End.
  - Generic, medium-level “universal” language

Front End Parser

- Front End will parse the input program.
  - All computer languages come with parsing rules.
  - These parsing rules are the grammar (syntax) for the language.
  - This produces a parse tree, which is the Intermediate Representation.

Example:



Back End

- Once the program is in an Intermediate Representation:
  - Step through the IR, considering each piece of the parse tree.
  - Figure out which machine instruction template matches each piece.
  - Use the MIPS look-up table to find the corresponding instruction in binary.

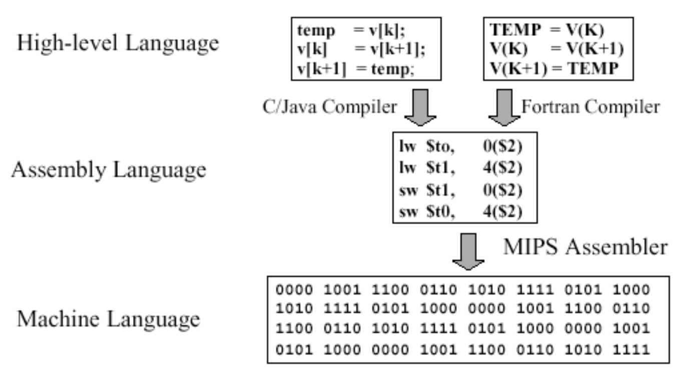
	IR	*Assembly instruction*	*MIPS binary*
Example:	x = y + z	lw, $s, [z]	
		lw, $t, [y]	
		add, $d, $s, $t	0000 00ss ssst tttt dddd d000 0010 0000
		sw, $d, [x]	

Now we have a program in bits, which can be executed by the CPU!

Note: Often we need to optimize the code (to *make it faster*):

Lots of clever techniques to improve the code.

Example



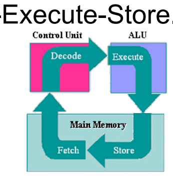
www.cise.ufl.edu/~mssz/ CompOrg/CDA-lang.html

Linking different programs

- Often different pieces of the program are built separately.
- Each piece can go through the compiler individually, to get separate executables. Need to put all this together somehow!
- Linker: Takes pieces of the program and puts them together into an executable.
  - Sometimes this is done as part of the compiler, sometimes separately.

Take-home message

- Understand the main components of the computer.
- Be familiar with the principles of Fetch-Decode-Execute-Store.



- Understand the role of machine language.
- Know the main components of the compiler (Front End, Back End, Intermediate Representation) and what purpose they serve.