Computer Systems 1
Lecture 07

Computer Architecture

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Topics

How computers developed

- Adding machines
- Machines that could add, subtract, multiply, divide
- Machines that could do fixed sequences of arithmetic
- Machines that could look at the results of arithmetic and then decide what to do next

Machine arithmetic

- Machines have long been used to help with arithmetic
- Some assist the human (abacus)
- Others perform arithmetic mechanically (Pascal's adder)
- Arithmetic with gears (19th century technology)
  - Video showing how carry propagation can be done with gears http://www.youtube.com/watch?v=YXMuJco8onQ
  - Video of Pascal calculator http://www.youtube.com/watch?v=3h71HAJWnVU
- Binary arithmetic with marbles (just for fun!)
  - http://www.youtube.com/watch?v=GcDshWmhF4A
  - http://www.youtube.com/watch?v=md0TlSjIags

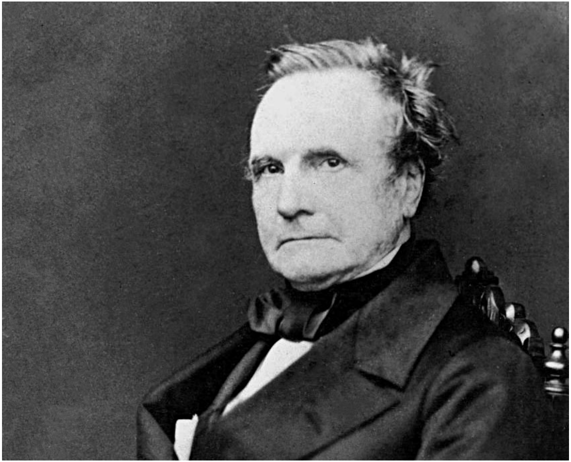
Three key ideas

1. Make a machine that performs a fixed sequence of arithmetic operations
2. Provide a way to change that sequence (set up the machine for a specific sequence)
   - Jacquard loom used punched cards
   - Babbage's Difference Engine: sequence of arithmetic operations to calculate functions for nautical tables
   - You configure the machine for a specific problem by defining the sequence of operations to perform
3. Make it possible for the machine to compare two numbers, and then decide what to do next
   - Babbage's Analytical Engine: the first general "Turing-complete" computer
   - Instead of computing a fixed sequence of operations, there is something like a conditional if x<y then ... else ...

Charles Babbage (1791–1871)

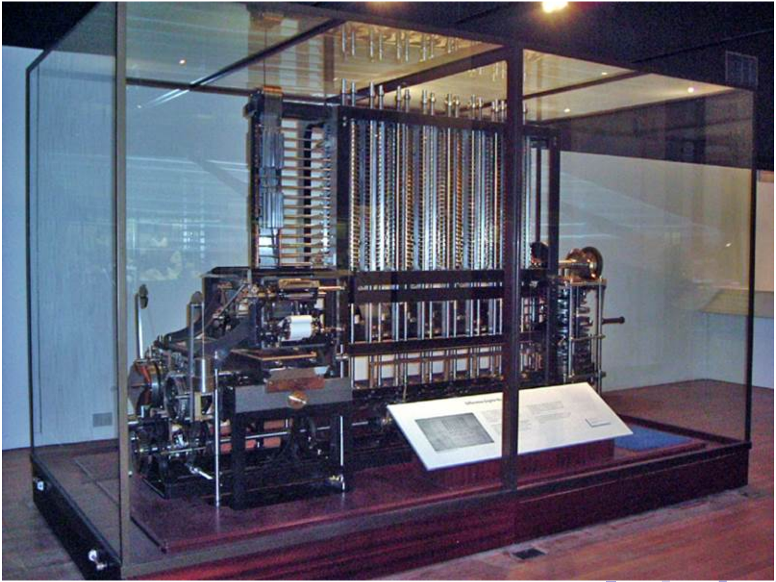
- British mathematician
- Campaigned to use Leibniz' notation for differentials $\frac{d\ f(x)}{dt}$ rather than Newton's notation $f'(x)$
- Noticed that tables (logarithms, sin, cos, etc.) contained many errors
- This led to navigation errors, and possibly loss of some ships
- Decided that only a machine could be accurate enough
- Designed the Difference Engine that could do fixed sequences of arithmetic
- Later designed the Analytical Engine that could look at the results of arithmetic and then decide what to do next

Charles Babbage



"Inventor of the computer"

Babbage's Difference Engine



Babbage's Engines

- Video of Difference Engine in Science Museum, London
  http://www.youtube.com/watch?v=jiRgdaknJCg
- Longer demo of reconstruction of Difference Engine in California
  http://www.youtube.com/watch?v=BlbQsKpq3Ak
- Video of a model of part of the Analytical Engine
  http://www.youtube.com/watch?v=QVxbNZWLP60

Computer Architecture

- Computer Architecture defines the structure and the machine language of a computer.
- This subject is in the middle of computer systems
  - At lower levels, we have physics, transistors, digital circuits
  - In the middle, computer architecture is implemented using digital circuits and supports compilers and operating systesm
  - At higher levels, we have operating systems, compilers, system software, network protocols, and applications
- Understanding the principles of computer architecture is central to computer science
- A practical benefit: understanding machine language will give you a deeper understanding of programming languages

The Language of Machines

- There are many programming languages
- Each machine has one fixed machine language
- How can there be many programming languages?
  - Each PL is translated to machine language by software called a compiler
- What is a computer?
  - A digital circuit (a piece of hardware, a machine) that executes programs

Machine language

- A fixed digital circuit can execute one fixed machine language
- Examples:
  - Intel Core or Pentium (actually, there is a family of Intel processors "x86" and their machine languages are related but not identical)
  - ARM
  - MIPS
  - Sparc
  - ... and many more
- The details of different machine languages are quite different
- But we will focus on principles common to all of them

What is machine language like?

- Very different from Python, Java, C, . . .
- The designer of a machine language has to "look both up and down":
  - Looking up, the machine language must be powerful enough to provide the foundation for operating systems and programming languages. Later, we'll see what this means.
  - Looking down, the machine language must be simple enough so that a digital circuit can execute it. Example: the RTM can execute very simple programs, with some help from you!
- Machine languages are also designed to make high performance possible
- But they are *not* intended to make programming as easy as possible!
- Today, we'll look at a simplified notation called assembly language; next time we'll look at the real machine language

Instructions

- A machine language provides *instructions*
- Analogous to statements in a programming language, with some differences
    - Statements can be complex: x := 2 * (a + b/c)
    - Instructions are simple: R2 := R1 + R3
    - Each instruction just performs one operation

Sigma16

- In this course we will study an architecture called Sigma16
- Sigma16 is designed to support several research projects at the University of Glasgow
- It's a research machine, not a commercial product
- There is a complete design, including a full digital circuit
- It hasn't been manufactured, but there are two implementations in software
  - An emulator, which you will use in this course
  - A simulator for the circuit

Why use Sigma16?

- Our focus is on ideas and principles
- Sigma16 illustrates all the main ideas, but avoids unnecessary complexity
- Example:
  - Sigma16 has just one word size — 16 bits — while commercial machines provide many
  - Most commercial computers have backward compatibility with previous versions, leading to great complexity
  - Legacy architectures use an approach called complex instruction set, a simpler reduced instruction set gives better performance — Sigma16 uses this.

Structure of a computer

All computers have several main subsystems

- The register file is a set of 16 "registers"; this is the set of registers in the RTM circuit. They are often named R0, R1, R2, ..., R15.
- A register is a circuit (a little machine) that can remember a 16-bit word
- The ALU (arithmetic and logic unit) is a circuit that can do arithmetic, such as addition, subtraction, comparison, and some other operations
- The memory can hold a large number of words. It's similar to the register file, but significantly slower and much larger
- The Input/Output can transfer data from the outside world to/from the memory

Register file

- There are 16 registers
- Each register holds a 16-bit word
- We'll write the words using hexadecimal

R0	0000
R1	fffe
R2	13c4
⋮	⋮
R14	03c8
R15	0020

What are the registers actually?

- Recall the register transfer machine circuit
- It contains four registers, each holding 4 bits
- Sigma16 is just the same, but with 16 registers and each holds 16 bits
- Each 16-bit register is 16 copies of the reg1 circuit
- Why program with registers, not variables like sum, count, x, etc?
    - In machine language we are programming directly with the hardware in the computer

The RTM instructions

- The RTM circuit can execute two instructions
  - R2 := R1 + R0 ; add two registers and load result
  - R1 := 8 ; load a constant
- We'll begin with the corresponding Sigma16 instructions

The add instruction

- Think of the registers as variables
- Examples:
  - add R5,R2,R3 ; means R5 := R2 + R3
  - add R12,R1,R7 ; means R12 := R1 + R7
- General form:
  - `add dest,op1,op2` where dest, op1, op2 are registers
  - The two operands are added, the result is placed in the destination
  - Meaning: `dest` := `op1` + `op2`
- Everything after a semicolon ; is a comment

Registers can hold variables

- We often think of a variable as a box that can hold a number
- A register can hold a variable!
- An add instruction (or sub, mul, div) is like an assignment statement
- add R2,R8,R2 means R2 := R8 + R2
  1. Evaluate the right hand side R8 + R2
  2. The operands (R8, R2) are not changed
  3. Overwrite the left hand side (destination) (R2) with the result
  4. The old value of the destination is destroyed
  5. It is not a mathematical equation
  6. It is a command to do an operation and put the result into a register, overwriting the previous contents
- Assignment is often written R2 := R8 + R2
- The := operator means *assign*, and does not mean *equals*

Notation and terminology

Why write a notation like add R5,R2,R3 instead of R5 := R2 + R3?

- It's actually more consistent because *every* instruction will be written in this form: a keyword for the operation, followed by the operands
- The notation is related closely to the way instructions are represented in memory, which we'll see later

A simple program

The problem:

- Given three integers in R1, R2, R3
- Goal: calculate the sum R1+R2+R3 and put it in R4

Solution:

```
add  R4,R1,R2    ;  R4 := R1+R2   (this is a comment)
add  R4,R4,R3    ;  R4 := (R1+R2) + R3
```

More arithmetic instructions

There are instructions for the basic arithmetic operations

```
add  R4,R11,R0    ; R4 := R11 + R0
sub  R8,R2,R5     ; R8 := R2 - R5
mul  R10,R1,R2    ; R10 := R1 * R2
div  R7,R2,R12    ; R7 := R2 / R12
```

Every arithmetic operation takes its operands from registers, and loads the result into a register

Example

- Suppose we have variables a, b, c, d
- R1=a, R2=b, R3=c, R4=d
- We wish to compute R5 = (a+b) * (c-d)

```
add    R6,R1,R2       ; R6 := a + b
sub    R7,R3,R4       ; R7 := c - d
mul    R5,R6,R7       ; R5 := (a+b) * (c-d)
```

Good comments make the code easier to read!

General form of arithmetic instruction

General form: op d,a,b

op	operation: $+ - \times \div$
d	destination register: where the result goes
a	first operand register
b	second operand register

Meaning: $R_d := R_a \ (op) \ R_b$

Example: `add R5,R2,R12 ; R5 := R2+R12`

Register R0 and R15 are special!

- You should not use R0 or R15 to hold ordinary variables!
- R0 always contains 0
  - Any time you need the number 0, it's available in R0
  - You cannot change the value of R0
  - add R0,R2,R3 ; does nothing — R0 will not change
  - add R5,R2,R3 ; fine - you can change all other registers
  - It is legal to use R0 as the destination, but it will still be 0 after you do it!
- R15 holds status information
  - Some instructions place additional information in R15 (is the result negative? was there an overflow?)
  - Therefore the information in R15 is transient
  - R15 is for temporary information; it's not a safe place to keep long-term data

Limitation of register file: it's small

- The register file is used to perform calculations
- In computing somethine like `x := (2*a + 3*b) / (x-1)`, all the arithmetic will be done using the register file
- But it has a big limitation:
  - There are only 16 registers
  - And most programs need more than 16 variables!
- Solution: the memory is large and can hold far more data than the register file

Memory

- The memory is similar to the register file: it is a large collection of words
- A variable name (x, sum, count) refers to a word in memory
- Some differences between memory and register file:
    - The memory is much larger: 65,536 locations (the register file has only 16)
    - The memory cannot do arithmetic
- So our strategy in programming:
    - Keep data permanently in memory
    - When you need to do arithmetic, copy a variable from memory to a register
    - When finished, copy the result from a register back to memory

Registers and memory

- The register file
  - 16 registers
  - Can do arithmetic, but too small to hold all your variables
  - Each register holds a 16-bit word
  - Names are R0, R1, R2, . . ., R15
  - You can do arithmetic on data in the registers
  - Use registers to hold data temporarily that you're doing arithmetic on
- The memory
  - 65,536 memory locations
  - Each memory location holds a 16-bit word
  - Each memory location has an address 0, 1, 2, . . ., 65,535
  - The machine cannot do arithmetic on a memory location
  - Use memory locations to store program variables permanently. Also, use memory locations to store the program.

Copying a word between memory and register

There are two instructions for accessing the memory

- load copies a variable from memory to a register
  - `load R2,x[R0]` copies the variable `x` from memory to register R2
  - R2 := x
  - R2 is changed; x is unchanged
- store copies a variable from a register to memory
  - `store R3,y[R0]` copies the word in register R3 to the variable `y` in memory
  - y := R3
  - y is changed; R3 is unchanged
- Notice that we write [R0] after a variable name. Later we'll see the reason.

An assignment statement in machine langauge

x := a+b+c

```
load    R1,a[R0]       ; R1 := a
load    R2,b[R0]       ; R2 := b
add     R3,R1,R2       ; R3 := a+b
load    R4,c[R0]       ; R4 := c
add     R5,R3,R4       ; R5 := (a+b) + c
store   R5,x[R0]       ; x := a+b+c
```

1. Use load to copy variables from memory to registers
2. Do arithmetic with add, sub, mul, div
3. Use store to copy result back to memory

Why do we have registers and memory

- The programmer has to keep track of which variables are currently in registers
- You have to use load and store instructions to copy data between the registers and memory
- Wouldn't it be easier just to get rid of the distinction between registers and memory? Do all the arithmetic on memory
- Short answer:
  - Yes, it's possible to design a computer that way
  - But it makes the computer *very much slower*
  - With modern circuits, a computer without load and store instructions (where you do arithmetic on memory locations) would run between 100 and 1,000 times slower

Constants: the lea instruction

- The RTM has an instruction that loads a constant into a register
- Use the lea instruction
- lea R2,57[R0] loads the constant 57 into R2: $R2 := 57$
- *Actually, lea does much more than this — later we'll see some advanced applications*
- General form: lea R_d,const[R0]
- You must write [R0] after the constant; we'll see the reason for this later on

Example using lea

```
; R3 := R1 + 39*R2

    lea    R4,39[R0]      ; R4 := 39
    mul    R3,R4,R2       ; R3 := 39 * R2
    add    R3,R1,R3       ; R3 := R1 + (39*R2)
```

Stopping the program

The last instruction should be

```
     trap    R0,R0,R0    ; halt
```

This tells the computer to halt; it stops execution of the program

Defining variables

To define variables x, y, z and give them initial values

```
x     data   34    ; x is a variable with initial value 34
y     data    9    ; y is initially 9
z     data    0    ; z is initially 0
abc   data  $02c6  ; specify initial value as hex
```

The data statements should come *after* all the instructions in the program (we'll see why later)

A complete example program

```
; Program Add
; A minimal program that adds two integer variables

; Execution starts at location 0, where the first instruction will be
; placed when the program is executed.

      load    R1,x[R0]    ; R1 := x
      load    R2,y[R0]    ; R2 := y
      add     R3,R1,R2    ; R3 := x + y
      store   R3,z[R0]    ; z := x + y
      trap    R0,R0,R0    ; terminate

; Static variables are placed in memory after the program

x     data  23
y     data  14
z     data  99
```

https://xkcd.com/1437/