

1 Introduction

1.0 Course Introduction

Computer Architecture is designing the organization and hardware to meet goals and functional requirements. (by *Hennesy & Patterson, CAAQA 5th edition*)

Computer Architecture

- ISA (Instruction Set Architecture)
- Micro-architecture
- Hardware implementation

This COURSE mainly focus on ISA and Micro-architecture.

Why study this COURSE

- Technology is always changing
- Requirements are always changing.
- Understand computer performances.

1.1 Technology and Trends

Moore's Law (摩尔定律) : The number of transistors on a microchip doubles every two years, though the cost of computers is halved. (by *Gordan Moore, 1965*)

Dennard Scaling (登纳德缩放定律) : As transistors get smaller, their power density stays constant. In other words, power usage of transistors stays in proportion with area or both voltage and current scale (downward) with length. (by *Robert H. Dennard, 1974*)

- The *Dennard Scaling* has expired in 2005.
- The *Moore's Law* still has effect currently.

The History of Computer Architecture: 4 revolutions.

- **Revolution I:** the invention of micro-processors.
- **Revolution II:** extract implicit instruction-level parallelism. (*RISC*)
- **Revolution III:** support explicit data & thread level parallelism. (*multi-core*)
- **Revolution IV:** focus on heterogeneous processing (*Graphics Processing Units, GPU or Special-purpose logic*).

Current Trend:

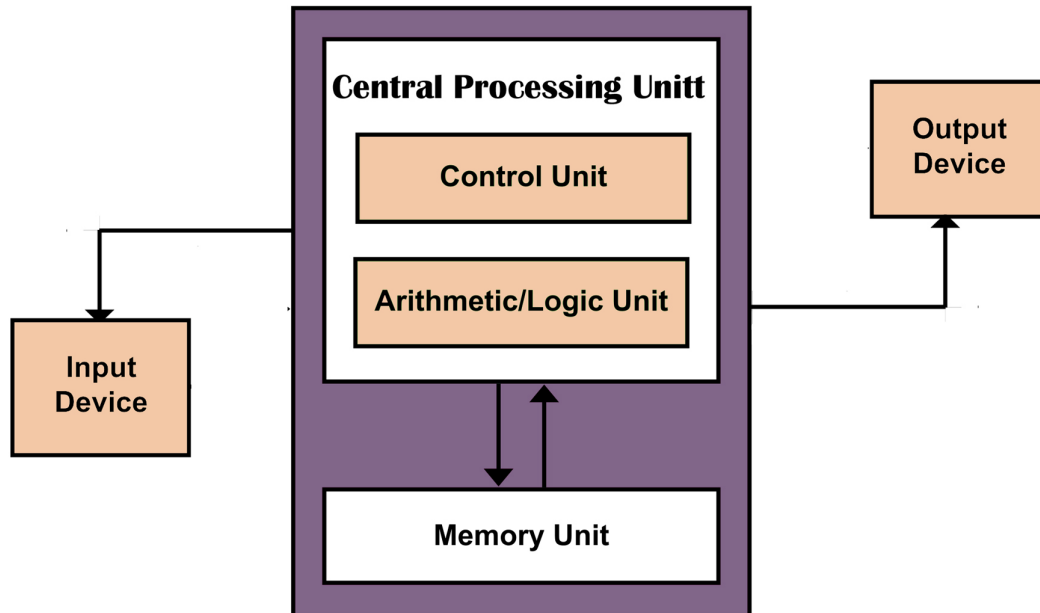
- Complex processor designs;
- Parallelism at chip level;
- Power-conscious designs;
- Specialization: domain-specific processors;
- Open source hardware: RISC-V;
- Security.

1.2 The Basic Architecture of Computer

ENIAC (1946, *UPenn*) The first computer. (*no memory*)

EDVAC (1951, *UPenn*) The first computer with memory, based on *Von Neumann Architecture*.

Von Neumann Architecture (冯·诺依曼体系结构)



Von Neumann Architecture

The introduction of the Von Neumann Architecture can refer to notes of *EI209: Computer Organization*.

- **Stored Program** (存储程序) : The programs (instructions) are in the *memory*, and the computer executes sequentially.
- **Take memory as center** (以存储器为中心) : This can free *CPU* from input/output work, enable *CPU* to do other work when outer devices communicate with *memory*.

1.3 The Execution of a Program

Languages in Computer

- High-level Language (高级语言) (*such as C, C++, etc.*)
- Assembly Language (汇编语言) (*by compiler*)
- Machine Language (机器语言) (*in binary*) (*by assembler*)

Memory capacity (存储容量) : the capacity of memory. Unit: *bit, byte(B), KB, MB, GB, TB, PB*.

Register (寄存器)

- General Register: R_0, R_1, \dots, R_{n-1} , save the intermediate result in a calculation.
- Special Register.
 - **MAR**: Memory Address Register, connected to the *address bus*, is the only way for CPU to communicate with *address bus* (**read-only**). Both an *instruction address* and a *data address* can be stored in MAR.
 - **MDR**: Memory Data Register, is connected to the *data bus*. Data can go in both directions, to and from memory (**read and write**).
 - **PC**: Program Counter, store the current instruction's address. When the instruction is executed, PC will go forward automatically to the next instruction's address.
 - **IR**: Instruction Register, store the current instruction's code.

Main Memory (主存储器) : *memory, MAR and MDR*.

Controller (控制器) : *CU* (控制单元) , *PC* and *IR*.

The Execution of an Instruction

- Get the instruction from *main memory* according to *PC* and put it into *IR*;
- *CU* analyze the instruction in *IR*;
- *CU* control the other part of the computer to finish the instruction (by sending *signal*).

The Execution of a Program execute each instruction in a certain order (usually *sequential*).

Instruction Length (指令字长) : The length of an instruction.

Storage Length (存储字长) : The length of *MDR*.

Word Length of a Computer (机器字长) : The length of data that the controller can handle at one time.

1.4 The Performance of Computer

Performance Metrics

- **Latency** (延迟) (execution time, response time) (执行时间、响应时间) : time to complete a *given* task, or a *fixed* task.

$$Performance \propto \frac{1}{Latency} = \frac{1}{Execution Time}$$

- **Throughput** (吞吐率) (bandwidth) (带宽) : the rate of completion of tasks; number of tasks per unit time.
 - Exploit parallelism for throughput, not latency. As a result, *improving bandwidth is easier than improving latency*.

Performance Speedup Ratio (性能加速比)

$$R = \frac{Performance_X}{Performance_Y} = \frac{Execution Time_Y}{Execution Time_X}$$

where, R is the performance speedup ratio.

[Example] $Performance_X = 1.5$, $Performance_Y = 1.0$, then $R = 1.5$, we can say:

- X is 1.5 times faster than Y ;
- The speedup ratio of X to Y is 1.5;
- The performance of X improves 50% comparing to Y .

CPU Performance

$$CPU Time = CT \times \sum_{i=1}^n (IC_i \times CPI_i) = CT \times IC \times \overline{CPI}$$

where

- $CPU Time$: execution time;
- IC : total number of instructions;
- IC_i : number of instructions executed (instruction count) in instruction group i ;
- CPI_i : number of average clock cycles per instruction in instruction group i ;
- \overline{CPI} : average clock cycles per instruction.
- CT : duration of processor clock.

How to Improve CPU Performance (each part):

- **IC**: Instruction Count.
 - Compiler optimizations (*constant folding*)
 - ISA (*more complex instructions*)

- **CPI**: Cycle Per Instruction.
 - Microarchitecture (*pipelining, Out-of-order execution, branch prediction*)
 - Compiler (*instruction scheduling*)
 - ISA (*simpler instructions*)
- **CT**: Clock Time.
 - Technology (smaller transistors)
 - ISA (Simple instructions that can be easily decoded)
 - Microarchitecture (simple architecture)

Misunderstandings

- Only focus on **CT**.
- Only focus on **MIPS** (Million Instructions Per Second) or **FLOPS** (Floating Point Operation Per Second)
- **CPI** depends on **CT**.
 - In fact, **CT** and **CPI** are irrelevant.

1.5 Principles of Architecture Design

Principles of Computer Architecture

- Take advantage of parallelism.
 - System level: multi-processors, multi-disks, multi-channels.
 - Processor level: operate on multiple instructions at once (*pipelining, superscalar issue*)
 - Circuit level: operate on multiple bits at once (*carry-lookahead ALU*)
- Focus on the common case. (*RISC design principle*)
 - Common case first. (大概率事件优先)
 - *Amdahl's law*. (阿姆达尔定律)
- Principle of locality. (*Catches*)
 - Spatial and Temporal Locality.
 - 90% of the program executing in 10% of the code.

Amdahl's Law

$$S = \frac{1}{(1 - P) + P/s}$$

where,

- P : proportion of running time affected by optimization.
- S : total speedup ratio. (总加速比)
- s : the speedup ratio in a part (可加速部分加速比) , $s = n$ in parallelization conditions.

Amdahl's Law requires extremely parallel code to take advantage of large multi-processors.

Amdahl's Law is not suitable for *the quantity-extensible problem* (规模可扩展问题) .

Little's Law is a theorem that determines the average number of items in a stationary queuing system based on the average waiting time of an item within a system and the average number of items arriving at the system per unit of time.

$$L = \lambda W$$

where,

- L : items in the system;
- λ : average arrival rate; the average number of items arriving at the system per unit of time;
- W : average wait time.

Assumptions: system is in steady state, i. e., average arrival rate = average departure rate.

Works on any queuing system and even systems of system.

Application to get high λ (throughput), we need either:

- low W (latency per request);
- high L (service requests in parallel).