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COMPUTER ORGANISATION
(TỔ CHỨC MÁY TÍNH)

Computer Organisation

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Policies for students

- These contents are only used for students PERSONALLY.
- Students are NOT allowed to modify or deliver these contents to anywhere or anyone for any purpose.

Road Map: **Part II**

- **Performance**
- **Assembly Language**
- **Processor: Datapath**
- **Processor: Control**
- **Pipelining**
- **Cache**

- Performance definition
- Factors affecting performance
- Amdahl's law
- A tour of benchmarks

Performance: **Two Viewpoints**

- "Computer X is ***faster*** than Computer Y" is an ambiguous statement:
  - "Fast" can be interpreted in several ways

1. Fast = **Response Time**
   - The duration of a program execution is shorter

2. Fast = **Throughput**
   - More work can be done in the same duration

- We focus on the 1st viewpoint in this section

Performance: **Comparison**

- Performance is in "***units of things-per-second***"
  - Bigger is better
- Response time is in "***number of seconds***"
  - Smaller is better

$$performance_x = \frac{1}{time_x}$$

- Speedup ***n***, between ***x*** and ***y*** is

$$Speedup = \frac{time_y}{time_x} = \frac{performance_x}{performance_y}$$

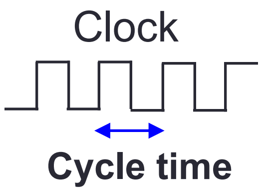
Execution Time: **Refining Definition**

- There are different measures of execution time in computer performance:
- **Elapsed time** (aka wall-clock time)
  - Counts everything (including disk and memory accesses, I/O, etc.)
  - Not too good for comparison purposes.
- **CPU time**
  - Doesn’t include I/O or time spent running other programs.
  - Can be broken up into ***system time*** and ***user time***.
- Our focus: **User CPU time**
  - Time spent executing the lines of code in the program

Execution Time: **Clock Cycles**

- Instead of reporting execution time in seconds, we often use **clock cycles** (basic time unit in machine).

$$\frac{\text{seconds}}{\text{program}} = \frac{\text{cycles}}{\text{program}} \times \frac{\text{seconds}}{\text{cycle}}$$



- **Cycle time** (or cycle period or clock period)
  - Time between two consecutive rising edges, measured in seconds.
- **Clock rate** (or clock frequency)

  = 1 / cycle-time

  = number-of-cycles / second

  - Unit is in Hz, 1 HZ = 1 cycle / second

Execution Time: **Version 1.0**

$$\frac{\text{seconds}}{\text{program}} = \frac{\text{cycles}}{\text{program}} \times \frac{\text{seconds}}{\text{cycle}}$$

- Therefore, to improve performance (everything else being equal), you can do the following:
  - ↓ Reduce the number of cycles for a program, or
  - ↓ Reduce the clock cycle time, or said in another way,
  - ↑ Increase the clock rate

Exercise 1: **Clock Cycle & Clock Rate**

- Program P runs in 10 seconds on computer A, which has a 400 MHz clock.
- Suppose we are trying to build a new machine B that will run this program in 6 seconds. Unfortunately, the increase in clock rate has an averse effect on the rest of the CPU design, causing machine B to require 1.2 times as many clock cycles as machine A for the same program. What clock rate should we target at to hit our goal?

- ANSWER:

Let C be the number of clock cycles required for that program.

For A: Time = 10 sec. = C × 1 / 400MHz

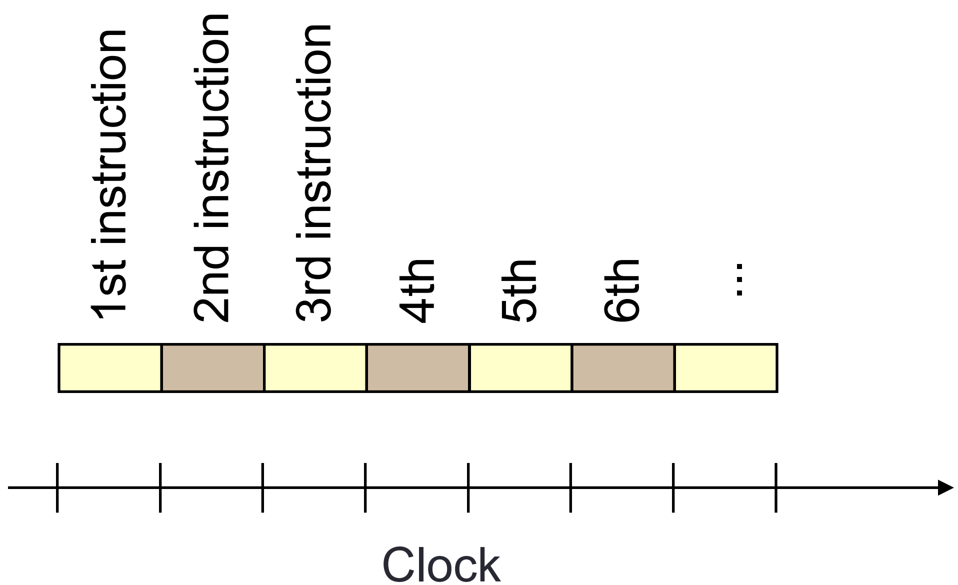
For B: Time = 6 sec. = (1.2 × C) × 1 / ***clock_rateB***

Therefore, ***clock_rateB*** = ?

Clock Cycles: **Proportional?**

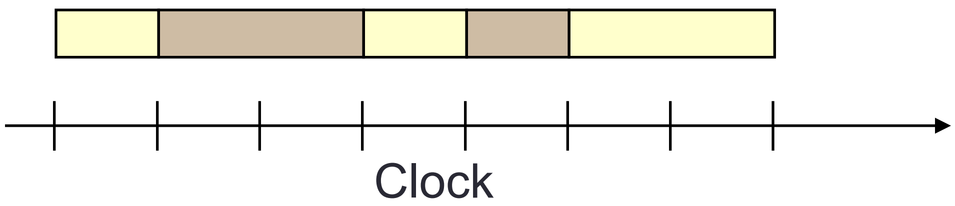
- An execution consists of **x** number of instructions
  - Does it mean we need **n * X** cycles to finish it?

→ Number of cycles is proportional to number of instructions?



Clock Cycles: **Inst Type Dependent**

- Different instructions take different amount of time to finish:



- For example:
  - ***Multiply*** instruction may take longer than an ***Add*** instruction.
  - ***Floating-point*** operations take longer than ***integer*** operations.
  - Accessing ***memory*** takes more time than accessing ***registers***

Execution Time: **Introducing CPI**

- A given program will require

Some number of instructions (machine instructions)

↓ × **average Cycle per Instruction (CPI)**

Some number of cycles

↓ × **cycle time**

Some number of seconds

- We use the *average* CPI as different instructions take different number of cycles to finish

Execution Time: **Version 2.0**

- Average Cycle Per Instruction (CPI)

CPI = (CPU time × Clock rate) / Instruction count

= Clock cycles / Instruction count

$$\text{CPU time} = \frac{\text{Seconds}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Cycle}}$$

$$\text{CPI} = \sum_{k=1}^{n} \text{CPI}_k \times F_k \quad \textbf{where} \quad F_k = \frac{I_k}{\text{Instruction count}}$$

I_k = Instruction frequency

Performance: **Influencing Factors**

Program compiles into Binary	Process	Binary executes on Machine
Compiler **ISA**	Factors	**Hardware Organization**
#instructions **Avg CPI**	Performance aspects influenced by factors	**Cycle Time** **CPI**

Program → Binary: **Factors**

- **Compiler:**
  - Different compilers may generate different binary codes
    - e.g. gnu vs intel c/c++ compiler
  - Different optimization may generate different binary codes
    - e.g. different optimization level in ***gnu c compiler***
- **Instruction Set Architecture:**
  - The same high level statement can be translated differently depending on the ISA
    - e.g. same C program under ***Intel*** machine vs ***Sunfire*** server

Exercise 2: **Impact of Compiler**

- Given a program P, a compiler can generate 2 different binary on a target machine. On that machine, there are 3 classes of instructions: Class A, Class B, and Class C, and they require 1, 2, and 3 cycles respectively.
- First binary has 5 instructions: **2 of A, 1 of B, and 2 of C**.
  Second binary has 6 instructions: **4 of A, 1 of B, and 1 of C**.

1. Which code is faster? By how much?
2. What is the (average) CPI for each code?

- ANSWER:

  Let T be the cycle time.

  Time(code1) = $(2\times1 + 1\times2 + 2\times3) \times T = 10T$

  Time(code2) = $(4\times1 + 1\times2 + 1\times3) \times T = 9T$

  Time(code1)/Time(code2) =

  CPI(code1) =

  CPI(code2) =

Execution of Binary Code: **Factors**

- **Machine**
  - More accurately the hardware implementation
  - Determine **cycle time** and **cycle per instruction**
- **Cycle Time**:
  - Different clock frequency (e.g. 2ghz vs 3.6ghz)
- **Cycle Per Instruction:**
  - Design of internal mechanism (e.g. specific accelerator to improve floating point performance)

Exercise 3: **Impact of Machine**

- Suppose we have 2 implementations of the same ISA, and a program is run on these 2 machines.
- Machine A has a clock cycle time of 10 ns and a CPI of 2.0. Machine B has a clock cycle time of 20 ns and a CPI of 1.2.

> 1. Which machine is faster for this program? By how much?

- ANSWER:

Let N be the number of instructions.

Machine A: Time = N $\times$ 2.0 $\times$ 10 ns

Machine B: Time =

Performance(A)/Performance(B) = Time(B)/Time(A)

=

Exercise 4: **All Factors** (1/4)

- You are given 2 machine designs M1 and M2 for performance benchmarking. Both M1 and M2 have the same ISA, but different hardware implementations and compilers. Assuming that the clock cycle times for M1 and M2 are the same, performance study gives the following measurements for the 2 designs.

Instruction class	For M1		For M2	
	CPI	No. of instructions executed	CPI	No. of instructions executed
A	1	3,000,000,000,000	2	2,700,000,000,000
B	2	2,000,000,000,000	3	1,800,000,000,000
C	3	2,000,000,000,000	3	1,800,000,000,000
D	4	1,000,000,000,000	2	900,000,000,000

Exercise 4 (2/4)

a) What is the CPI for each machine?

Let Y = 1,000,000,000,000

CPI(M1) = $(3Y \times 1 + 2Y \times 2 + 2Y \times 3 + Y \times 4) / (3Y + 2Y + 2Y + Y)$
$= 17Y / 8Y =$ **2.125**

CPI(M2) =
=

b) Which machine is faster? By how much?

Let C be cycle time.

Time(M1) = $2.125 \times (8Y \times C)$
Time(M2) =

M1 is faster than M2 by

Exercise 4 (3/4)

c) To further improve the performance of the machines, a new compiler technique is introduced. The compiler can simply eliminate all class D instructions from the benchmark program without any side effects. (That is, there is no change to the number of class A, B and C instructions executed in the 2 machines.) With this new technique, which machine is faster? By how much?

Let Y = 1,000,000,000,000; Let C be cycle time.

$CPI(M1) = (3Y\times1 + 2Y\times2 + 2Y\times3) / (3Y + 2Y + 2Y) = 13Y / 7Y = 1.857$

$CPI(M2) =$

$=$

$Time(M1) = 1.857 \times (7Y \times C)$

$Time(M2) =$

M1 is faster than M2 by

Exercise 4 (4/4)

d) Alternatively, to further improve the performance of the machines, a new hardware technique is introduced. The hardware can simply execute all class D instructions in zero times without any side effects. (There is still execution for class D instructions.) With this new technique, which machine is faster? By how much?

Let Y = 1,000,000,000,000; Let C be cycle time.

CPI(M1) = $(3Y\times1 + 2Y\times2 + 2Y\times3 + Y\times0) / (3Y + 2Y + 2Y + Y)$
$= 13Y / 8Y = 1.625$

CPI(M2) =
=

Time(M1) = $1.625 \times (8Y \times C)$

Time(M2) =

M1 is faster than M2 by

Summary: **Key Concepts**

- Performance is specific to a particular program on a specific machine
  - Total execution time is a consistent summary of performance
- For a given architecture, performance increase comes from:
  - Increase in clock rate (without adverse CPI effects)
  - Improvement in processor organization that lowers CPI
  - Compiler enhancement that lowers CPI and/or instruction count

Pitfall:
Expecting improvement in one aspect of a machine's performance to affect the total performance.

Amdahl's Law (1/3)

- **Pitfall:** Expecting the improvement of one aspect of a machine to increase performance by an amount proportional to the size of the improvement.
- Example:
  - Suppose a program runs in 100 seconds on a machine, with multiply operations responsible for 80 seconds of this time. How much do we have to improve the speed of multiplication if we want the program to run 4 times faster?

100 (total time) = 80 (for multiply) + UA (unaffected)

100/4 (new total time) =

➔Speedup =

Amdahl's Law (2/3)

- Example (continued):
  - How about making it 5 times faster?

100 (total time) = 80 (for multiply) + UA (unaffected)

100/5 (new total time) =

➔Speedup =

Amdahl's Law (3/3)

- **Amdahl's law**:
  - Performance is limited to the non-speedup portion of the program

- Execution time after improvement

  = Execution time of unaffected part

  + (Execution time of affected part / Speedup)

- **Corollary of Amdahl's law:**
  - Optimize the common case first!

Exercise 5: **Amdahl's Law**

- Suppose we enhance a machine making all floating-point instructions run **five times** faster. If the execution time of some benchmark before the floating-point enhancement is **12 seconds**, what will the speedup be if **half of the 12 seconds** is spent executing floating-point instructions?

Time =

Speedup =

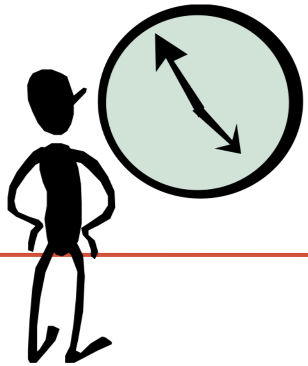
Exercise 6: **Amdahl's Law**

- We are looking for a benchmark to show off the **new floating-point unit** described in the previous example, and we want the overall benchmark to show a **speedup of 3**. One benchmark we are considering **runs for 100 seconds** with the old floating-point hardware. How much of the execution time would floating-point instructions have to account for in this program in order to yield our desired speedup on this benchmark?

Speedup =

Time_FI =

BENCHMARK



A quick tour of benchmarks in the world

(For your own reading)

Benchmark Program: **Overview**

- It is not easy to evaluate and compare the performance between computer system
  - Our discussion focused only on processor performance

  ➔Much more complicated if we bring in other aspects of a system (e.g. Memory, Graphic, Network etc)

- We will look at a few well known benchmarks

Benchmarks: **Industry Standards**

- SPEC benchmark suites:
  - **SPECint**, **SPECfp**: For processor + memory + compiler
  - **SPECjvm2008**: For Java performance
  - Many others
- EEMBC benchmark suites
  - **ANDBench**: For Android performance
  - **DPIBench**: For system and network performance
  - etc
- **N**umerical **A**erodynamic **S**imulation (**NAS**):
  - From NASA
  - Massively parallel benchmark: For computer cluster

Benchmarks: **Simple Benchmark**

- These benchmarks can be found easily on the web
- **Linpack:**
  - Linear Algebra Solver
  - Used in the SuperComputer ranking
- **Dhrystone** / **Whetstone**:
  - Small program to test integer / floating performance
- **Tak Function**:
  - To test recursion optimization

Benchmarks: **For PC Users**

- There are also benchmarks for PC users
  - Focus mainly on graphics performance
- **3DMark**
  - Designed to stress test performance of Direct X
- **PCMark**
  - Used by Microsoft Windows
- **Unigine Benchmarks**
  - “Heaven” Benchmark: For tessellation test
- **Peacekeeper**
  - Web browser test

Reading Assignment

- Evaluating Performance
  - Read up COD sections 4.1 – 4.3 (3rd edition)
  - Read up COD section 1.4 (4th edition)

Q&A