# CHAPTER 6

Performance of a Computer

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# DEFINING PERFORMANCE

- When we say one computer has better performance than another, what do we mean?

| | | |
|---|---|---|
| The desktop computer that gets the job done first. | The total **time** required for the computer to complete a task | **Response time or Execution time** |
| A datacenter that completed the most jobs during a day. (Parallel) | the number of **tasks** completed per unit time. | **Throughput or Bandwidth** |

# RESPONSE TIME AND THROUGHPUT

- Do the following changes to a computer system increase throughput, decrease response time, or both?
  - 1. Replacing the processor in a computer with a faster version
  - 2. Adding additional processors to a system that uses multiple processors for separate tasks—for example, searching the World Wide Web

# RELATIVE PERFORMANCE

Performance of one Computer ?

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

Compare performance of 2 computers ?

$$\frac{Performance_x}{Performance_y} = \frac{Executiontime_y}{Executiontime_x} = n$$

"X is *n* time faster than Y"

Example:

A program takes10s on computer A and 15s on computer B, compare the performance of computer A and B.

$$\frac{Performance_x}{Performance_y} = \frac{Executiontime_y}{Executiontime_x} = n$$

$$\frac{Executiontime_B}{Executiontime_A} = \frac{15s}{10s} = 1.5$$

$$Executiontime_B = 1.5 \times Executiontime_A$$

Answer: A is 1.5 times faster than B
or B is 1.5 times slower than A

## EXAMPLE

Computer C's performance is 4 times faster than the performance of computer B, which runs a given application in 28 seconds. How long will computer C take to run that application?

## SOLUTION

$$Executiontime_B = 4 \times Executiontime_C$$

$$28\ seconds = 4 \times Executiontime_C$$

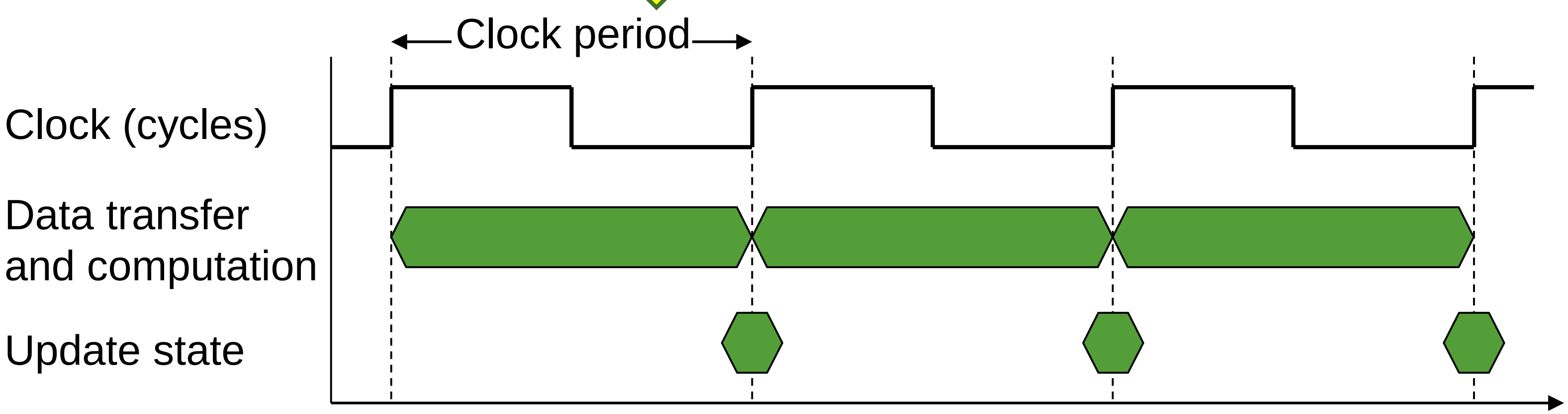
$$Executiontime_C = 7\ seconds$$

# CLOCK

duration of a clock cycle

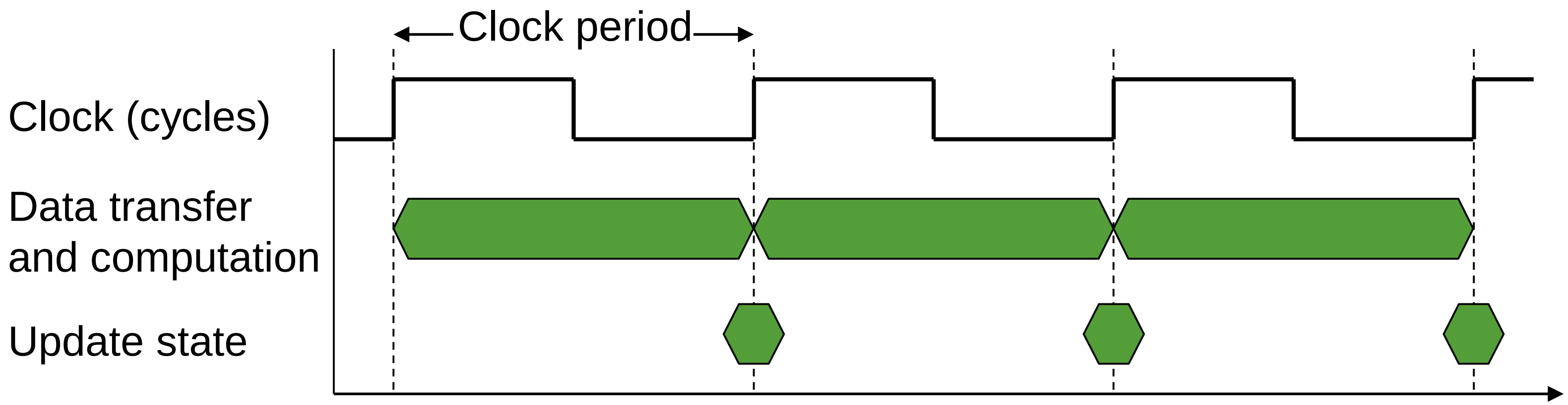
Unit = seconds

clock periods = clock cycles = ticks = clock ticks = clocks = cycles




- Operation of digital hardware governed by a constant-rate clock
- Determines when events take place in the hardware

# CLOCK FREQUENCY OR CLOCK RATE




clock periods
= clock rate

- Inverse of the clock periods
- The number of clocks per a second
- Unit = Hertz (Hz) or clocks per second

Example:

clock period = 250ps = 0.25ns = $250 \times 10^{-12}$s

clock rate = $\frac{1}{clock\ period}$ = 4.0GHz = 4000MHz = $4.0 \times 10^{9}$Hz

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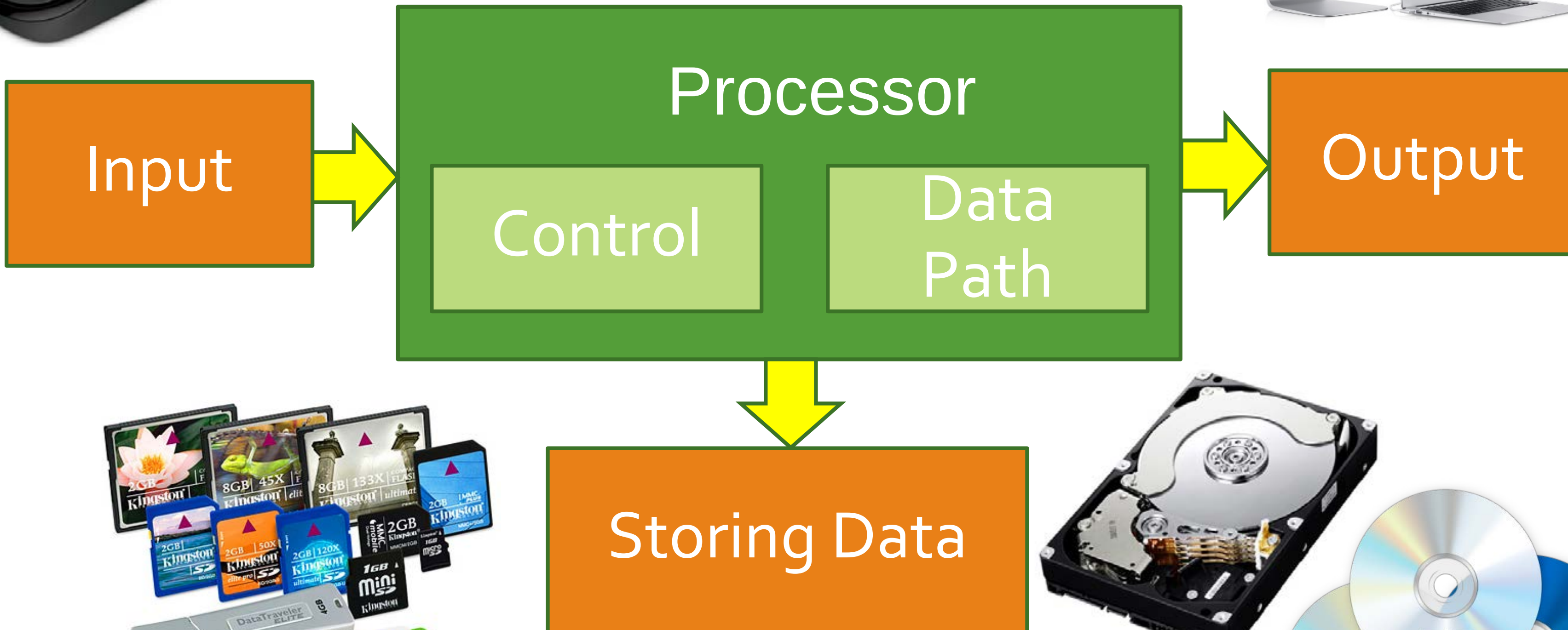
**Specifications**

| | | | |
|---|---|---|---|
| Up to 1.7GHz dual-core Intel Core i7 processor | Up to 2.9GHz dual-core Intel Core i7 processor | Up to 2.8GHz quad-core Intel Core i7 processor | Up to 3.5GHz quad-core Intel Core i7 processor |

# PREFIXES

Tera (T) = 1,000,000,000,000(trillion)/ $10^{12}$
Giga (G) = 1,000,000,000(billion)/ $10^{9}$
Mega(M) = 1,000,000(million)/ $10^{6}$
Kilo (K) = 1,000(thousand)/ $10^{3}$
Hecto(H) = 100(hundred)/ $10^{2}$
Deka (DA) = 10(ten)/ $10^{1}$
Unit = 1
Deci(d) = .1 (tenth)/ $10^{-1}$
Centi(c) = .01(hundredth)/ $10^{-2}$
Milli(m) = .001(thousandth)/ $10^{-3}$
Micro(mu) = .000001(millionth)/ $10^{-6}$
Nano(n) = .000000001(billionth)/ $10^{-9}$
Pico (p) = .000000000001(trillionth)/ $10^{-12}$

# Components of a Computer




# MEASURING PERFORMANCE

TIME : a PROGRAM

clock time, response time, elapsed time, or execution time.

The total time to complete a task

Including disk accesses, memory accesses, input/output (I/O) activities, operating system overhead—everything

User can experience this time

**CPU** execution time or **CPU** time

User CPU time (Program)

System CPU time (OS)

the time the **CPU** spends computing for a task

# CPU TIME (FOR A PROGRAM)

$$CPU\ execution\ time = CPU\ clock\ cycles \times \boldsymbol{Clock\ cycle\ time}$$

$$CPU\ execution\ time = \frac{CPU\ clock\ cycles}{\boldsymbol{Clock\ Rate}}$$

- Improving performance of Hardware by
  - Reducing number of clock cycles
  - Increasing clock rate
- Hardware designer must often trade off clock rate against cycle count

EXAMPLE:

Our favorite program runs in 10 seconds on computer A, which has a 2 GHz clock. We are trying to help a computer designer build a computer, B, which will run this program in 6 seconds. The designer has determined that a substantial increase in the clock rate is possible, but this increase will affect the rest of the CPU design, causing computer B to require 1.2 times as many clock cycles as computer A for this program. What clock rate should we tell the designer to target?

SOLUTION:

$$\boxed{CPU\ execution\ time = \frac{CPU\ clock\ cycles}{\mathbf{Clock\ Rate}}}$$

Computer A : $CPU\ Time_A = 10\ seconds,$

$$Clock\ rate_A = 2\ GHz$$

$$10\ Sec = \frac{CPU\ clock\ cycles_A}{2\ GHz} \text{ ---------- } \mathbf{A}$$

Computer B : $CPU\ Time_B \quad = 6\ seconds$

$CPU\ clock\ cycles_{\boldsymbol{B}} = 1.2 \times CPU\ clock\ cycles_{\boldsymbol{A}}$

$Clock\ rate_B\ =\ ?$

From

$$\boxed{CPU\ execution\ time = \frac{CPU\ clock\ cycles}{\boldsymbol{Clock\ Rate}}}$$

$$6\ Sec = \frac{1.5 \times CPU\ clock\ cycles_A}{Clock\ rate_B} \text{------}\ \mathbf{B}$$

$$\frac{\mathbf{A}}{\mathbf{B}} = \frac{10\ Sec}{6\ Sec} = \frac{CPU\ clock\ cycles_A}{2\ GHz} \times \frac{Clock\ rate_B}{1.2 \times CPU\ clock\ cycles_A}$$

$$Clock\ rate_B = \frac{10 \times 1.2 \times 2 \times 10^9\ Hz}{6} = 4 \times 10^9 GHz$$

# INSTRUCTION PERFORMANCE

- computer had to execute the instructions to run the program
- the execution time must depend on the number of instructions in a program
- For easy, think about execution time is that it equals the number of instructions executed multiplied by the average time per instruction. Therefore ->

$$CPU\ clock\ cycle = \frac{Instruction\ for}{a\ program} \times CPI$$

<u>**Instruction for a program**</u> = <u>**instruction count**</u> = the number of instruction executed by the program

Average <u>**clock cycles per instruction**</u>

# EXAMPLE:

- Suppose we have two implementations of the same instruction set architecture. Computer A has a clock cycle time of 250 ps and a CPI of 2.0 for some program, and computer B has a clock cycle time of 500 ps and a CPI of 1.2 for the same program. Which computer is faster for this program and by how much?

# SOLUTION:

$$CPU\ execution\ time = CPU\ clock\ cycles \times Clock\ cycle\ time$$

$$CPU\ clock\ cycle = \frac{Instruction\ for}{a\ program} \times CPI$$

$$Clock\ cycle\ time_A = 250\ ps$$
$$Clock\ cycle\ time_B = 500\ ps$$

$$CPU\ Clock\ Cycle_A = I \times 2.0$$
$$CPU\ Clock\ Cycle_B = I \times 1.2$$

$$CPU\ execution\ time = CPU\ clock\ cycles \times \mathbf{Clock\ cycle\ time}$$

$$CPU\ execution\ time_A = I \times 2.0 \times 250\ ps$$
$$CPU\ execution\ time_B = I \times 1.2 \times 500\ ps$$

Which computer is faster for this program and by how much?

$$\frac{Performance_x}{Performance_y} = \frac{Executiontime_y}{Executiontime_x} = n$$

$$\frac{CPU\ Performance_A}{CPU\ Performance_B} = \frac{I \times 1.2 \times 500\ ps}{I \times 2.0 \times 250\ ps} = 1.2$$

Thus, computer A is 1.2 times as fast as computer B for this program.

$$CPU\ execution\ time = CPU\ clock\ cycles \times Clock\ cycle\ time$$

$$CPU\ clock\ cycle = \begin{matrix} Instruction\ for \\ a\ program \end{matrix} \times CPI$$

$$CPU\ execution\ time = \begin{matrix} Instruction \\ Count \end{matrix} \times CPI \times \begin{matrix} Clock\ cycle \\ time \end{matrix}$$

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$$CPU\ execution\ time = \frac{CPU\ clock\ cycles}{Clock\ Rate}$$

$$CPU\ clock\ cycle = \begin{matrix} Instruction\ for \\ a\ program \end{matrix} \times CPI$$

$$CPU\ execution\ time = \frac{Instruction\ Count \times CPI}{Clock\ Rate}$$

# EXAMPLE:

- A compiler designer is trying to decide between two code sequences for a particular computer. The hardware designers have supplied the following facts:

| | Instruction Class | | |
|---|---|---|---|
| | A | B | C |
| CPI | 1 | 2 | 3 |

For a particular high-level language statement, the compiler writer is considering two code sequences that require the following instruction counts:

| Code Sequence | Instruction Class | | |
|---|---|---|---|
| | A | B | C |
| 1 | 2 | 1 | 2 |
| 2 | 4 | 1 | 1 |

Which code sequence executes the most instructions?

**SOLUTION**

Sequence 1 has 2+1+2 = 5 instructions

Sequence 2 has 4+1+1 = 6 instructions

Therefore, sequence 2 has more instructions.

# Which will be faster?

**SOLUTION**

$$CPU\ execution\ time = CPU\ clock\ cycles \times Clock\ cycle\ time$$

One computer with two codes -> so clock cycle time will be the same for each code. -> Compare the number of clock

$$CPU\ clock\ cycle = \frac{Instruction\ for}{a\ program} \times CPI$$

$$CPU\ clock\ cycle = \sum_{i=1}^{n} Instruction \times CPI$$

$CPU\ clock\ cycle_1 = (2 \times 1) + (1 \times 2) + (2 \times 3)$ = 10 cycles

$CPU\ clock\ cycle_2 = (4 \times 1) + (1 \times 2) + (1 \times 3)$ = 9 cycles

Therefore, the code sequence 2 is faster.

What is the CPI for each sequence?

**SOLUTION**

$$\boxed{CPI = \frac{CPU\ Clock\ Cycle}{Instruction\ Count}}$$

$$CPI_1 = \frac{CPU\ Clocl\ Cycle_1}{Instruction\ Count_1} = \frac{10}{5} = 2.0$$

$$CPI_2 = \frac{CPU\ Clocl\ Cycle_2}{Instruction\ Count_2} = \frac{9}{6} = 1.5$$

## CONCLUSION

Always bear in mind that the only complete and reliable measure of computer performance is **TIME.**

| Components of performance | Units of measure |
|---|---|
| CPU execution time (for a program) | Seconds (for the program) |
| Instruction count | The number of Instructions executed for the program |
| Clock cycles per instruction (CPI) | The number of clock cycles per instruction (Average ) |
| Clock cycle time | Seconds (per clock cycle) |

# MEASUREMENT

- **CPU EXECUTION TIME** -> running the program
- **INSTRUCTION COUNT** -> depend on hardware architecture and command used, so we have to use software tools that profile the execution or by using a simulator of the architecture, or use hardware counter, included in most processor.
- **CPI** -> depends on a wide variety of design details in the computer, including both the memory system and the processor structure. Thus, CPI varies by application, as well as among implementations with the same instruction set.
- **CLOCK CYCLE TIME** -> hardware spec = usually published as part of the documentation for a computer

# UNDERSTANDING PERFORMANCE

- **Algorithm**
  - Determines number of operations executed
- **Programming language, compiler, architecture**
  - Determine number of machine instructions executed per operation
- **Processor and memory system**
  - Determine how fast instructions are executed
- **I/O system (including OS)**
  - Determines how fast I/O operations are executed

# AMDAHL'S LAW

- Amdah's Law defines speed up

$$Speedup = \frac{Performance\ using\ enhancement}{Performance\ without\ using\ enhancement}$$

$$Speedup = \frac{Execution\ time\ without\ using\ enhancement}{Execution\ time\ using\ enhancement}$$

- The performance gain that can be obtaind by improving some portion of a computer.
- The execution time using the original computer with the enhanced mode will be the time spent using the unenhanced portion plus the time using the enhancement

The execution time of the program after making the improvement is given by the following simple equation known as **Amdahl's law**:

$$\begin{array}{c}\textit{Execution time}\\ \textit{After enhancement}\end{array} = \frac{\begin{array}{c}\textit{Execution time}\\ \textit{affected by}\\ \textit{enhancement}\end{array}}{\begin{array}{c}\textit{Amount of}\\ \textit{improve}\end{array}} + \begin{array}{c}\textit{Execution time}\\ \textit{unaffected}\end{array}$$

EXAMPLE

Suppose a program runs in 100 seconds on a computer, with multiply operations responsible for 80 seconds of this time. How much do I have to improve the speed of multiplication if I want my program to run five times faster?

SOLUTION

$$20\ sec = \frac{80\ sec}{n} + (100 - 80\ sec)$$

$$0 = \frac{80\ sec}{n}$$

Since we want the performance to be five times faster, the new execution time should be 20 seconds,

*no amount* by which we can enhance-multiply to achieve a fivefold increase in performance, if multiply accounts for only 80% of the workload

# EXAMPLE

Suppose that we want to enhance the processor used for Web serving. The new processor is 10 times faster on computation in the web serving application than the original processor. Assuming that the original processor is busy with computation 40% of the time and is waiting for I/O 60% of the time, what is the overall speedup gained by incorporating the enhancement ?

$$Speedup = \frac{Execution\ time\ without\ using\ enhancement}{Execution\ time\ using\ enhancement}$$

$$\begin{matrix} Execution\ time \\ After\ enhancement \end{matrix} = \frac{\begin{matrix} Execution\ time \\ affected\ by \\ enhancement \end{matrix}}{\begin{matrix} Amount\ of \\ improve \end{matrix}} + \begin{matrix} \text{Execution time} \\ \text{unaffected} \end{matrix}$$

$$Speedup = \frac{100}{\frac{40}{10} + 60} = \frac{100}{64} = 1.56$$

# MISP (million instructions per second)

$$MISP = \frac{Instruction\ Count}{Execution\ time\ \times 10^6}$$

- MIPS is an instruction execution rate
- Faster computers have a higher MIPS rating, MIPS specifies performance inversely to execution time = matches intuition

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The relationship between MIPS, clock rate, and CPI

$$MISP = \frac{Instruction\ Count}{\frac{Instruction\ Count \times CPI}{Clock\ rate} \times 10^6} = \frac{Clock\ rate}{CPI \times 10^6}$$

# LIMITATION

- MIPS specifies the instruction execution rate but does not take into account the capabilities of the instructions.
  - We cannot compare computers with different instruction sets using MIPS, since the instruction counts will certainly differ
- MIPS varies between programs on the same computer
  - a computer cannot have a single MIPS rating.

## EXAMPLE

| Measurement | Computer A | Computer B |
|---|---|---|
| Instruction count | 10 billion | 8 billion |
| Clock rate | 4 GHz | 4 GHz |
| CPI | 1.0 | 1.1 |

Which computer has the higher MIPS rating?

## SOLUTION

$$\boxed{MISP = \frac{Clock\ rate}{CPI \times 10^6}}$$

$$MISP_A = \frac{4 \times 10^9}{1.0 \times 10^6}$$

$$= 4 \times 10^3$$

$$MISP_B = \frac{4 \times 10^9}{1.1 \times 10^6}$$

$$= 3.64 \times 10^3$$

A has the higher MIPS rating than B

# EXAMPLE

| Measurement | Computer A | Computer B |
|---|---|---|
| Instruction count | 10 billion | 8 billion |
| Clock rate | 4 GHz | 4 GHz |
| CPI | 1.0 | 1.1 |

Which computer is faster?

## SOLUTION

$$CPU\ execution\ time = \frac{Instruction\ Count \times CPI}{Clock\ Rate}$$

$$CPU\ time_A = \frac{10 \times 10^9 \times 1.0}{4 \times 10^9} \qquad CPU\ time_B = \frac{8 \times 10^9 \times 1.1}{4 \times 10^9}$$

$$CPU\ time_A = 2.5\ seconds \qquad CPU\ time_B = 2.2\ seconds$$

Computer B is faster