



CE80655 Embedded Computer Systems Engineering

Class: Year 3 Computer Engineering

Lecture #2: Computer Abstractions #2

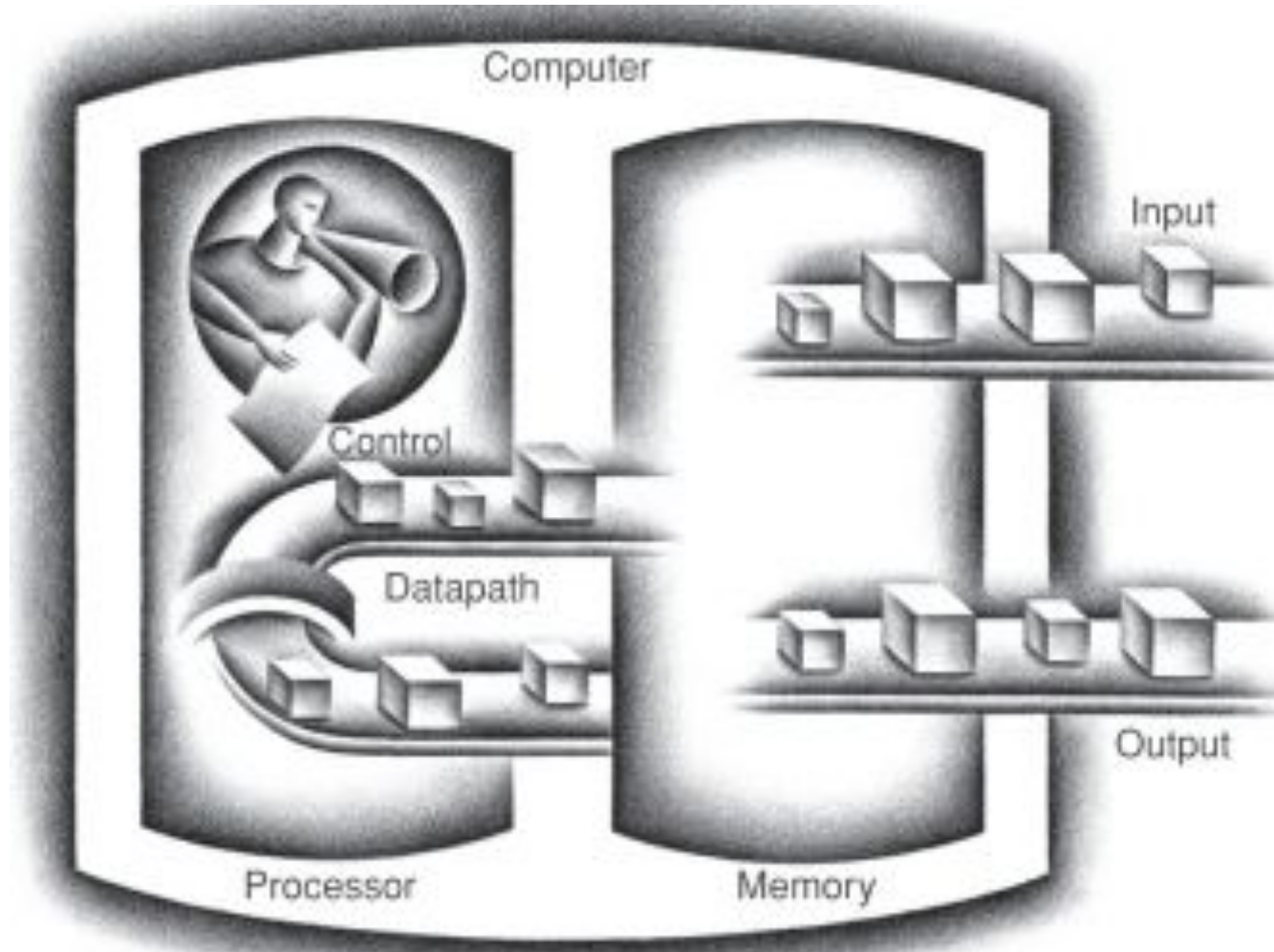
Department of Computer Engineering

02/02/2026 – 15/05/2026 (15 weeks)

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Five Classic Components of a Computer



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Lecture Outline

- **Defining Performance**
- CPU Performance and Its Factors
- Instruction Performance
- The Classic CPU Performance Equation



Defining Performance

$$\text{Performance}_X = \frac{1}{\text{Execution time}_X}$$

This means that for two computers X and Y, if the performance of X is greater than the performance of Y, we have

$$\begin{aligned} \text{Performance}_X &> \text{Performance}_Y \\ \frac{1}{\text{Execution time}_X} &> \frac{1}{\text{Execution time}_Y} \\ \text{Execution time}_Y &> \text{Execution time}_X \end{aligned}$$

That is, the execution time on Y is longer than that on X, if X is faster than Y.



Defining Performance

X is n times faster than Y” —or
equivalently “X is n times as fast as Y

$$\frac{\text{Performance}_X}{\text{Performance}_Y} = n$$

If X is n times as fast as Y, then the execution
time on Y is n times as long as it is on X:

$$\frac{\text{Performance}_X}{\text{Performance}_Y} = \frac{\text{Execution time}_Y}{\text{Execution time}_X} = n$$

Relative Performance

- Define Performance = $1/\text{Execution Time}$
- “X is n time faster than Y”

$$\begin{aligned} & \text{Performance}_X / \text{Performance}_Y \\ &= \text{Execution time}_Y / \text{Execution time}_X = n \end{aligned}$$

- Example: time taken to run a program
 - 10s on A, 15s on B
 - $\text{Execution Time}_B / \text{Execution Time}_A$
 $= 15\text{s} / 10\text{s} = 1.5$
 - So A is 1.5 times faster than B



Defining Performance

Relative Performance

If computer A runs a program in 10 seconds and computer B runs the same program in 15 seconds, how much faster is A than B?

EXAMPLE

We know that A is n times as fast as B if

$$\frac{\text{Performance}_A}{\text{Performance}_B} = \frac{\text{Execution time}_B}{\text{Execution time}_A} = n$$

ANSWER

Thus the performance ratio is

$$\frac{15}{10} = 1.5$$

and A is therefore 1.5 times as fast as B.



Defining Performance

ANSWER

In the above example, we could also say that computer B is 1.5 times *slower than* computer A, since

$$\frac{\text{Performance}_A}{\text{Performance}_B} = 1.5$$

means that

$$\frac{\text{Performance}_A}{1.5} = \text{Performance}_B$$



Lecture Outline

- Defining Performance
- **CPU Performance and Its Factors**
- Instruction Performance
- The Classic CPU Performance Equation

Measuring Execution Time

- Elapsed time
 - Total response time, including all aspects
 - Processing, I/O, OS overhead, idle time
 - Determines system performance
- CPU time
 - Time spent processing a given job
 - Discounts I/O time, other jobs' shares
 - Comprises user CPU time and system CPU time
 - Different programs are affected differently by CPU and system performance



CPU Performance and Its Factors

$$\text{CPU execution time for a program} = \text{CPU clock cycles for a program} \times \text{Clock cycle time}$$

Alternatively, because clock rate and clock cycle time are inverses,

$$\text{CPU execution time for a program} = \frac{\text{CPU clock cycles for a program}}{\text{Clock rate}}$$

CPU execution time (also called **CPU time**): The actual time the CPU spends computing for a specific task.

$$\begin{aligned} \text{Clock Cycle Time} &= 1 / \text{Clock Rate} \text{ or} \\ \text{Clock Rate} &= 1 / \text{Clock Cycle Time} \end{aligned}$$



CPU Performance and Its Factors

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Almost all computers are constructed using a **clock** that determines when events take place in the hardware.

**Clock Cycle Time = 1/ Clock Rate or
Clock Rate = 1/Clock Cycle Time**



CPU Performance and Its Factors

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These discrete time intervals are called **clock cycles** (or ticks, clock ticks, clock periods, clocks, cycles).

$$\begin{aligned} \text{Clock Cycle Time} &= 1 / \text{Clock Rate} \text{ or} \\ \text{Clock Rate} &= 1 / \text{Clock Cycle Time} \end{aligned}$$



CPU Performance and Its Factors

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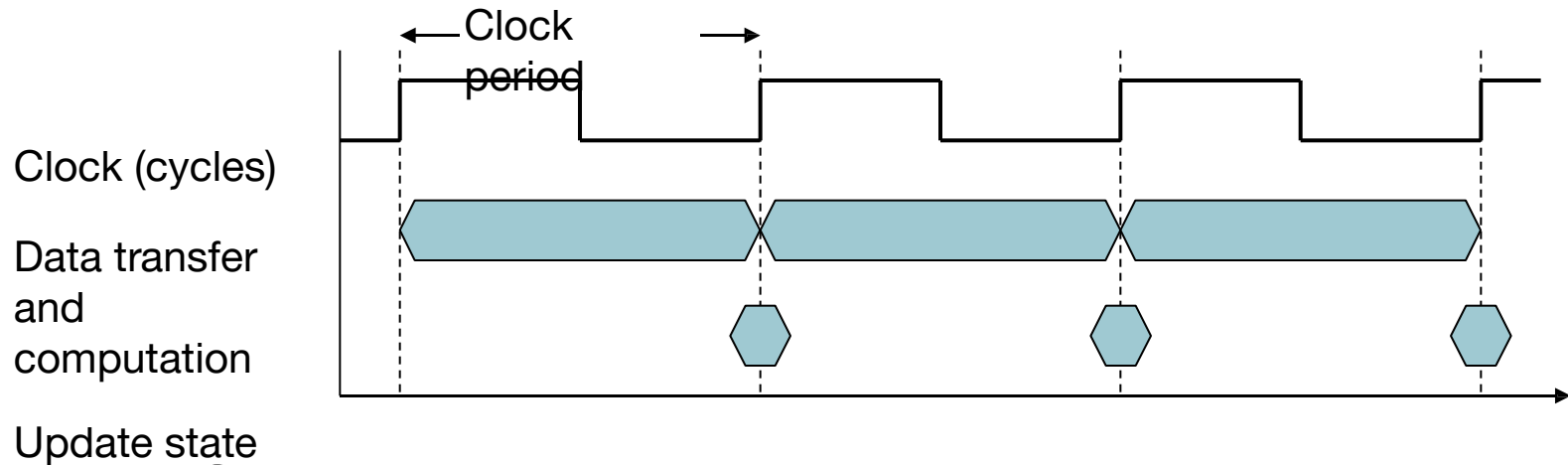
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$$\text{CPU execution time for a program} = \frac{\text{CPU clock cycles for a program}}{\text{Clock rate}}$$

Designers refer to the length of a clock period both as the time for a complete clock cycle (**e.g., 250 picoseconds, or 250 ps**) and as the clock rate (**e.g., 4 gigahertz, or 4 GHz**), which is the inverse of the clock period.

CPU Clocking

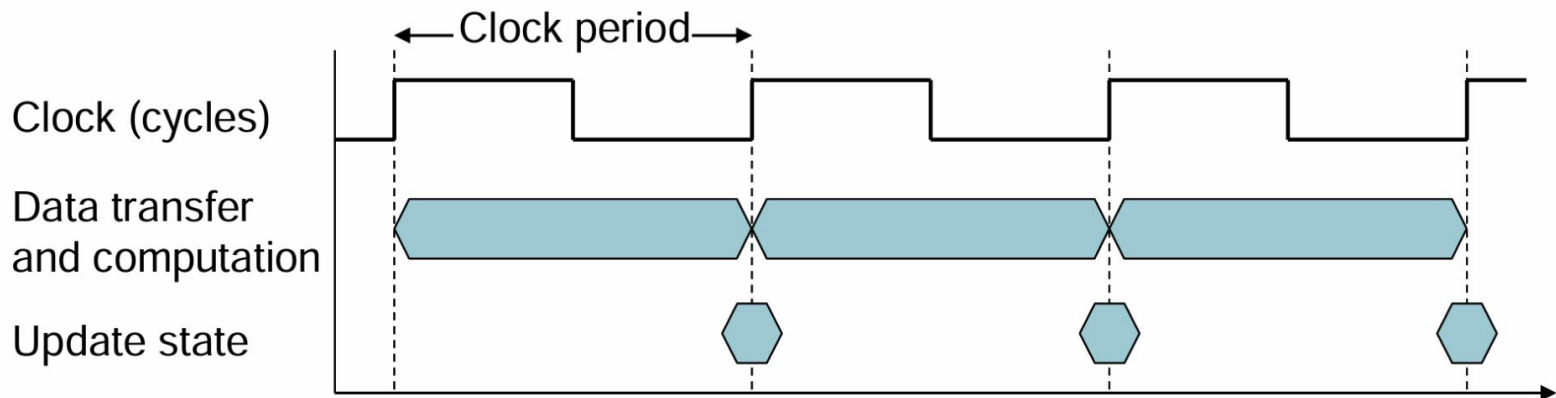
- Operation of digital hardware governed by a constant-rate clock



- Clock period: duration of a clock cycle
 - e.g., $250\text{ps} = 0.25\text{ns} = 250 \times 10^{-12}\text{s}$
- Clock frequency (rate): cycles per second
 - e.g., $4.0\text{GHz} = 4000\text{MHz} = 4.0 \times 10^9\text{Hz}$

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CPU Time

$$\begin{aligned}\text{CPU Time} &= \text{CPU Clock Cycles} \times \text{Clock Cycle Time} \\ &= \frac{\text{CPU Clock Cycles}}{\text{Clock Rate}}\end{aligned}$$

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

CPU Time Example

- Computer A: 2GHz clock, 10s CPU time
- Designing Computer B
 - Aim for 6s CPU time
 - Can do faster clock, but causes $1.2 \times$ clock cycles
- How fast must Computer B clock be?

$$\text{Clock Rate}_B = \frac{\text{Clock Cycles}_B}{\text{CPU Time}_B} = \frac{1.2 \times \text{Clock Cycles}_A}{6s}$$

$$\begin{aligned}\text{Clock Cycles}_A &= \text{CPU Time}_A \times \text{Clock Rate}_A \\ &= 10s \times 2\text{GHz} = 20 \times 10^9\end{aligned}$$

$$\text{Clock Rate}_B = \frac{1.2 \times 20 \times 10^9}{6s} = \frac{24 \times 10^9}{6s} = 4\text{GHz}$$



CPU Performance and Its Factors

EXAMPLE

Improving Performance

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?



CPU Performance and Its Factors

ANSWER

Let's first find the number of clock cycles required for the program on A:

$$\text{CPU time}_A = \frac{\text{CPU clock cycles}_A}{\text{Clock rate}_A}$$

$$10 \text{ seconds} = \frac{\text{CPU clock cycles}_A}{2 \times 10^9 \frac{\text{cycles}}{\text{second}}}$$

$$\text{CPU clock cycles}_A = 10 \text{ seconds} \times 2 \times 10^9 \frac{\text{cycles}}{\text{second}} = 20 \times 10^9 \text{ cycles}$$



CPU Performance and Its Factors

ANSWER

CPU time for B can be found using this equation:

$$\text{CPU time}_B = \frac{1.2 \times \text{CPU clock cycles}_A}{\text{Clock rate}_B}$$

$$6 \text{ seconds} = \frac{1.2 \times 20 \times 10^9 \text{ cycles}}{\text{Clock rate}_B}$$

$$\text{Clock rate}_B = \frac{1.2 \times 20 \times 10^9 \text{ cycles}}{6 \text{ seconds}} = \frac{0.2 \times 20 \times 10^9 \text{ cycles}}{\text{second}} = \frac{4 \times 10^9 \text{ cycles}}{\text{second}} = 4 \text{ GHz}$$

To run the program in 6 seconds, B must have twice the clock rate of A.



Lecture Outline

- Defining Performance
- CPU Performance and Its Factors
- **Instruction Performance**
- The Classic CPU Performance Equation



Instruction Performance

$$\text{CPU clock cycles} = \text{Instructions for a program} \times \frac{\text{Average clock cycles per instruction}}{\text{CPI}}$$

The term **clock cycles per instruction**, which is the average number of clock cycles each instruction takes to execute, is often abbreviated as **CPI**.

Instruction Count and CPI

$\text{ClockCycles} = \text{Instruction Count} \times \text{Cycles per Instruction}$

$\text{CPU Time} = \text{Instruction Count} \times \text{CPI} \times \text{Clock Cycle Time}$

$$= \frac{\text{Instruction Count} \times \text{CPI}}{\text{Clock Rate}}$$

- Instruction Count for a program
 - Determined by program, ISA and compiler
- Average cycles per instruction
 - Determined by CPU hardware
 - If different instructions have different CPI
 - Average CPI affected by instruction mix

CPI Example

- Computer A: Cycle Time = 250ps, CPI = 2.0
- Computer B: Cycle Time = 500ps, CPI = 1.2
- Same ISA
- Which is faster, and by how much?

$$\begin{aligned}\text{CPUTime}_A &= \text{Instruction Count} \times \text{CPI}_A \times \text{Cycle Time}_A \\ &= 1 \times 2.0 \times 250\text{ps} = 1 \times 500\text{ps} \leftarrow \text{A is faster...}\end{aligned}$$

$$\begin{aligned}\text{CPUTime}_B &= \text{Instruction Count} \times \text{CPI}_B \times \text{Cycle Time}_B \\ &= 1 \times 1.2 \times 500\text{ps} = 1 \times 600\text{ps}\end{aligned}$$

$$\frac{\text{CPUTime}_B}{\text{CPUTime}_A} = \frac{1 \times 600\text{ps}}{1 \times 500\text{ps}} = 1.2 \leftarrow \text{...by this much}$$

CPI in More Detail

- If different instruction classes take different numbers of cycles

$$\text{Clock Cycles} = \sum_{i=1}^n (\text{CPI}_i \times \text{Instruction Count}_i)$$

- Weighted average CPI

$$\text{CPI} = \frac{\text{Clock Cycles}}{\text{Instruction Count}} = \sum_{i=1}^n \left(\text{CPI}_i \times \frac{\text{Instruction Count}_i}{\text{Instruction Count}} \right)$$

Relative frequency

CPI Example

- Alternative compiled code sequences using instructions in classes A, B, C

Class	A	B	C
CPI for class	1	2	3
IC in sequence 1	2	1	2
IC in sequence 2	4	1	1

- Sequence 1: IC = 5

- Clock Cycles
 $= 2 \times 1 + 1 \times 2 + 2 \times 3$
 $= 10$
- Avg. CPI = $10/5 = 2.0$

- Sequence 2: IC = 6

- Clock Cycles
 $= 4 \times 1 + 1 \times 2 + 1 \times 3$
 $= 9$
- Avg. CPI = $9/6 = 1.5$



Instruction Performance

EXAMPLE

Using the Performance Equation

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?



Instruction Performance

ANSWER

We know that each computer executes the same number of instructions for the program; let's call this number I . First, find the number of processor clock cycles for each computer:

$$\text{CPU clock cycles}_A = I \times 2.0$$

$$\text{CPU clock cycles}_B = I \times 1.2$$

Now we can compute the CPU time for each computer:

$$\begin{aligned} \text{CPU time}_A &= \text{CPU clock cycles}_A \times \text{Clock cycle time} \\ &= I \times 2.0 \times 250 \text{ ps} = 500 \times I \text{ ps} \end{aligned}$$



Instruction Performance

ANSWER

Likewise, for B:

$$\text{CPU time}_B = I \times 1.2 \times 500 \text{ ps} = 600 \times I \text{ ps}$$

Clearly, computer A is faster. The amount faster is given by the ratio of the execution times:

$$\frac{\text{CPU performance}_A}{\text{CPU performance}_B} = \frac{\text{Execution time}_B}{\text{Execution time}_A} = \frac{600 \times I \text{ ps}}{500 \times I \text{ ps}} = 1.2$$

We can conclude that computer A is 1.2 times as fast as computer B for this program.



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- **The Classic CPU Performance Equation**



The Classic CPU Performance Equation

$$\text{CPU time} = \text{Instruction count} \times \text{CPI} \times \text{Clock cycle time}$$

or, since the clock rate is the inverse of clock cycle time:

$$\text{CPU time} = \frac{\text{Instruction count} \times \text{CPI}}{\text{Clock rate}}$$

The basic performance equation in terms of **instruction count (the number of instructions executed by the program)**, **CPI**, and **clock cycle time**.

We can use these formulas to compare two different implementations or to evaluate a design alternative if we know its impact on these three parameters.



The Classic CPU Performance Equation

EXAMPLE

Comparing Code Segments

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

	CPI for each 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 counts for each instruction class		
	A	B	C
1	2	1	2
2	4	1	1

Which code sequence executes the most instructions? Which will be faster? What is the CPI for each sequence?

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The Classic CPU Performance Equation

ANSWER

Sequence 1 executes $2 + 1 + 2 = 5$ instructions. Sequence 2 executes $4 + 1 + 1 = 6$ instructions. Therefore, sequence 1 executes fewer instructions.

We can use the equation for CPU clock cycles based on instruction count and CPI to find the total number of clock cycles for each sequence:

$$\text{CPU clock cycles} = \sum_{i=1}^n (\text{CPI}_i \times C_i)$$

This yields

$$\text{CPU clock cycles}_1 = (2 \times 1) + (1 \times 2) + (2 \times 3) = 2 + 2 + 6 = 10 \text{ cycles}$$

$$\text{CPU clock cycles}_2 = (4 \times 1) + (1 \times 2) + (1 \times 3) = 4 + 2 + 3 = 9 \text{ cycles}$$



The Classic CPU Performance Equation

ANSWER

So code sequence 2 is faster, even though it executes one extra instruction. Since code sequence 2 takes fewer overall clock cycles but has more instructions, it must have a lower CPI. The CPI values can be computed by

$$\text{CPI} = \frac{\text{CPU clock cycles}}{\text{Instruction count}}$$

$$\text{CPI}_1 = \frac{\text{CPU clock cycles}_1}{\text{Instruction count}_1} = \frac{10}{5} = 2.0$$

$$\text{CPI}_2 = \frac{\text{CPU clock cycles}_2}{\text{Instruction count}_2} = \frac{9}{6} = 1.5$$



The Classic CPU Performance Equation

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

FIGURE 1.15 The basic components of performance and how each is measured.

$$\text{Time} = \text{Seconds/Program} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock cycle}}$$



The Classic CPU Performance Equation

One alternative to time is **MIPS (million instructions per second)**. For a given program, MIPS is simply

$$\text{MIPS} = \frac{\text{Instruction count}}{\text{Execution time} \times 10^6}$$

$$\text{MIPS} = \frac{\frac{\text{Instruction count}}{\text{Instruction count} \times \text{CPI}} \times 10^6}{\text{Clock rate}} = \frac{\text{Clock rate}}{\text{CPI} \times 10^6}$$

Faster computers have a higher MIPS rating.

Performance Summary

The BIG Picture

$$\text{CPU Time} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{Clock cycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{Clock cycle}}$$

- Performance depends on
 - Algorithm: affects IC, possibly CPI
 - Programming language: affects IC, CPI
 - Compiler: affects IC, CPI
 - Instruction set architecture: affects IC, CPI, T_c



The Classic CPU Performance Equation

Consider the following performance measurements for a program:

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?
- Which computer is faster?



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