CSL7070: Computer Architecture

Lecture 4, 1st February 2023

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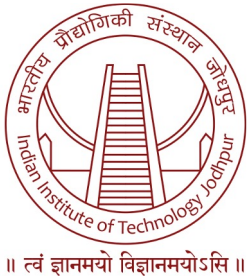

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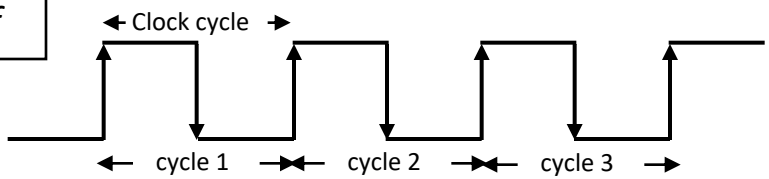
CPU Performance Evaluation (CPI)

- Most computers run synchronously utilizing a CPU clock running at a constant clock rate:

Or clock frequency: f



where: Clock rate = 1 / clock cycle

$f = 1/C$

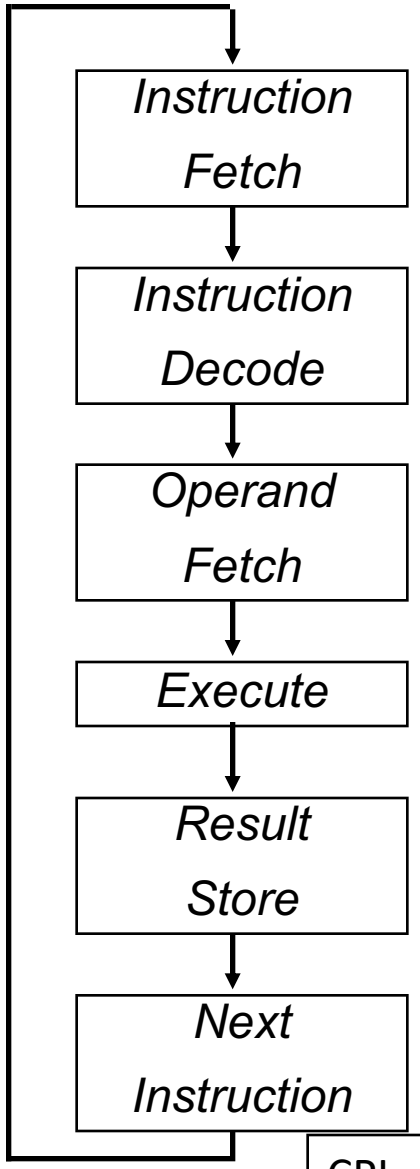
- The CPU clock rate depends on the specific CPU organization (design) and hardware implementation technology (VLSI) used.
- A computer machine (ISA) instruction is comprised of a number of elementary or micro operations which vary in number and complexity depending on the the instruction and the exact CPU organization (Design).
  - A micro operation is an elementary hardware operation that can be performed during one CPU clock cycle.
  - This corresponds to one micro-instruction in microprogrammed CPUs.
  - Examples: register operations: shift, load, clear, increment, ALU operations: add , subtract, etc.
- Thus: A single machine instruction may take one or more CPU cycles to complete termed as the Cycles Per Instruction (CPI).

Instructions Per Cycle = IPC = 1/CPI

- Average (or effective) CPI of a program: The average CPI of all instructions executed in the program on a given CPU design.

Cycles/sec = Hertz = Hz
MHz = 10^6 Hz GHz = 10^9 Hz

Generic CPU Machine Instruction Processing Steps



Obtain instruction from program memory

The Program Counter (PC) points to the instruction to be processed

Determine required actions and instruction size

Locate and obtain operand data

From data memory or registers

Compute result value or status

Deposit results in storage (data memory or register) for later use

Determine successor or next instruction

(i.e Update PC to fetch next instruction to be processed)

CPI = Cycles per instruction

Computer Performance Measures: Program Execution Time

- For a specific program compiled to run on a specific machine (CPU) "A", has the following parameters:
  - The total executed instruction count of the program. I
  - The average number of cycles per instruction (average CPI). CPI
  - Clock cycle of machine "A" C/CC

  Or effective CPI
- How can one measure the performance of this machine (CPU) running this program?
  - Intuitively the machine (or CPU) is said to be faster or has better performance running this program if the total execution time is shorter.
  - Thus the inverse of the total measured program execution time is a possible performance measure or metric:

Programs/second

$$\text{Performance}_A = 1 / \text{Execution Time}_A$$

Seconds/program

How to compare performance of different machines?

What factors affect performance? How to improve performance?

Comparing Computer Performance Using Execution Time

- To compare the performance of two machines (or CPUs) "A", "B" running a given specific program:

  $\text{Performance}_A = 1 / \text{Execution Time}_A$

  $\text{Performance}_B = 1 / \text{Execution Time}_B$

The two CPUs may target different ISAs provided the program is written in a high level language (HLL)

- Machine A is n times faster than machine B means (or slower? if n < 1) :

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

- Example: (i.e Speedup is ratio of performance, no units)

For a given program:

Execution time on machine A: $\text{Execution}_A = 1$ second

Execution time on machine B: $\text{Execution}_B = 10$ seconds

Speedup= $\text{Performance}_A / \text{Performance}_B = \text{Execution Time}_B / \text{Execution Time}_A$

$= 10 / 1 = 10$

The performance of machine A is 10 times the performance of machine B when running this program, or: Machine A is said to be 10 times faster than machine B when running this program.

CPU Execution Time: The CPU Equation

- A program is comprised of a number of instructions executed , I
  - Measured in: instructions/program

AKA Dynamic Executed Instruction Count

- The average instruction executed takes a number of *cycles per instruction (CPI)* to be completed.
  - Measured in: cycles/instruction, CPI

Or Instructions Per Cycle (IPC):
IPC = 1/CPI

- CPU has a fixed clock cycle time C = 1/clock rate
  - Measured in: seconds/cycle

$C = 1 / f$

- CPU execution time is the product of the above three parameters as follows:

Executed

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

$$T = I \times CPI \times C$$

T	I	CPI	C
execution Time per program in seconds	Number of instructions executed	Average CPI for program	CPU Clock Cycle

(This equation is commonly known as the CPU performance equation)

CPU Average CPI/Execution Time

For a given program executed on a given machine (CPU):

CPI = Total program execution cycles / Instructions count Executed (I)

(i.e average or effective CPI)

→ CPU clock cycles = Instruction count x CPI

(executed, I)

CPU execution time =

= CPU clock cycles x Clock cycle

= Instruction count x CPI x Clock cycle

T = I x CPI x C

T	I	CPI	C
execution Time per program in seconds	Number of instructions executed	Average or effective CPI for program	CPU Clock Cycle

(This equation is commonly known as the CPU performance equation)

CPI = Cycles Per Instruction

CPU Execution Time: Example

- A Program is running on a specific machine (CPU) with the following parameters:
  - Total executed instruction count: 10,000,000 instructions (I)
  - Average CPI for the program: 2.5 cycles/instruction.
  - CPU clock rate: 200 MHz. (clock cycle = C = 5×10^{-9} seconds) i.e 5 nanoseconds

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

- What is the execution time for this program:

CPU time = Instruction count x CPI x Clock cycle

= 10,000,000 x 2.5 x 1 / clock rate

= 10,000,000 x 2.5 x 5×10^{-9}

= 0.125 seconds

Nanosecond = nsec =ns = 10^{-9} second
MHz = 10^{6} Hz

$$T = I \times CPI \times C$$

Factors Affecting CPU Performance

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

$$T = I \times \text{CPI}_{\text{Average}} \times C$$

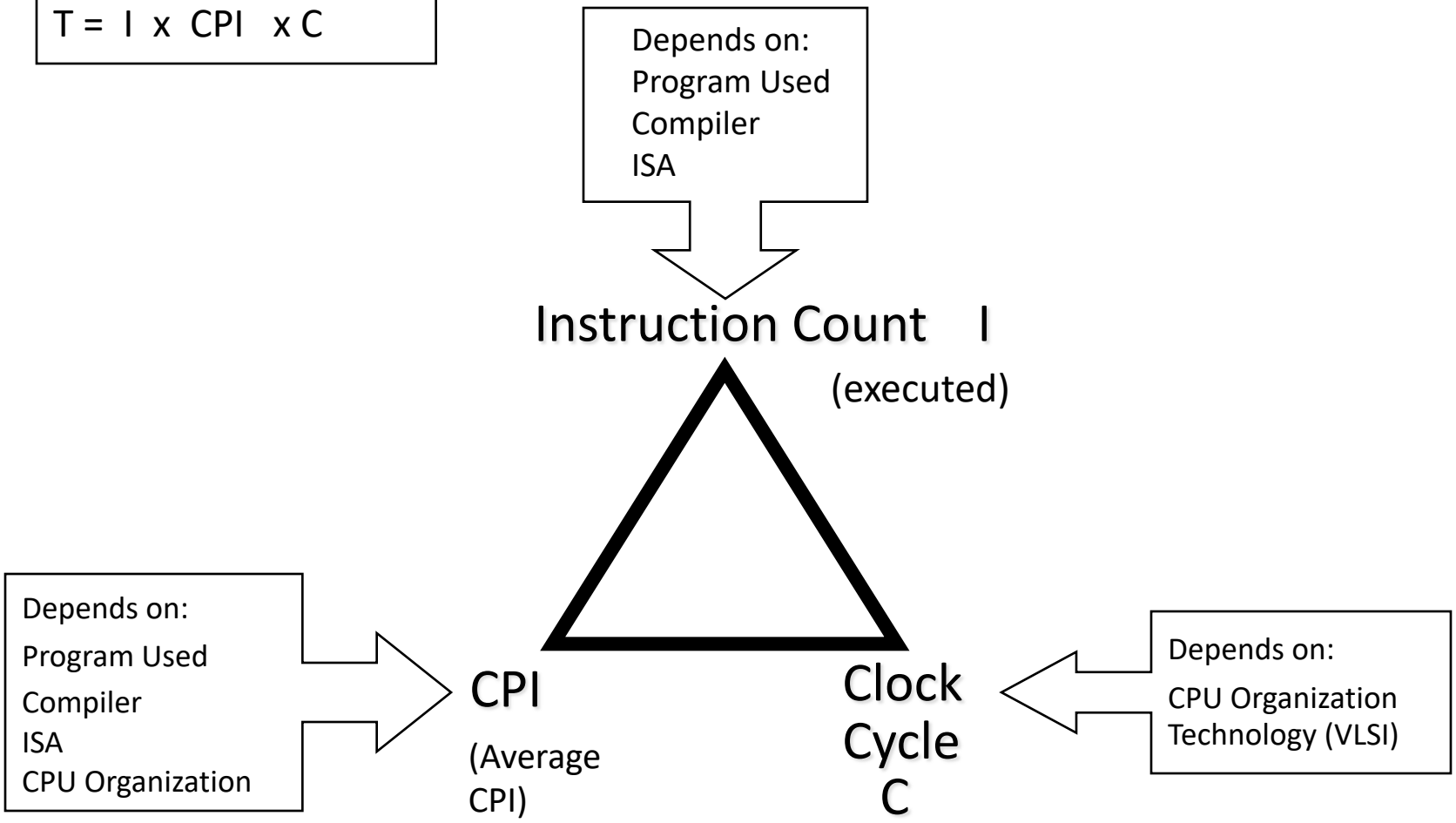
	Instruction Count	Cycles per Instruction	Clock Rate (1/C)
Program			
Compiler			
Instruction Set Architecture (ISA)			
Organization (CPU Design)			
Technology (VLSI)			

$$T = I \times CPI \times C$$

Aspects of CPU Execution Time

CPU Time = Instruction count executed x CPI x Clock cycle

T = I x CPI x C



Performance Comparison: Example

- From the previous example: A Program is running on a specific machine (CPU) with the following parameters:
  - Total executed instruction count, I: 10,000,000 instructions
  - Average CPI for the program: 2.5 cycles/instruction.
  - CPU clock rate: 200 MHz.

Thus: C = $1/(200 \times 10^6) = 5 \times 10^{-9}$ seconds

- Using the same program with these changes:
  - A new compiler used: New executed instruction count, I: 9,500,000
    New CPI: 3.0
  - Faster CPU implementation: New clock rate = 300 MHz

Thus: C = $1/(300 \times 10^6) = 3.33 \times 10^{-9}$ seconds

- What is the speedup with the changes?

$$\text{Speedup} = \frac{\text{Old Execution Time}}{\text{New Execution Time}} = \frac{I_{old} \times CPI_{old} \times \text{Clock cycle}_{old}}{I_{new} \times CPI_{new} \times \text{Clock Cycle}_{new}}$$

Speedup = $(10{,}000{,}000 \times 2.5 \times 5 \times 10^{-9}) / (9{,}500{,}000 \times 3 \times 3.33 \times 10^{-9})$

= .125 / .095 = 1.32

or 32 % faster after changes.

Clock Cycle = C = 1/ Clock Rate

$T = I \times CPI \times C$

Instruction Types & CPI

- Given a program with *n* types or classes of instructions executed on a given CPU with the following characteristics:

e.g ALU, Branch etc.

C_i = Count of instructions of type$_i$ executed

i = 1, 2, …. n

CPI_i = Cycles per instruction for type$_i$

Then:

Depends on CPU Design

CPI = CPU Clock Cycles / Instruction Count I

i.e average or effective CPI

Where:

Executed

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

Executed Instruction Count I = $\Sigma\ C_i$

T = I x CPI x C

Instruction Types & CPI: An Example

- An instruction set has three instruction classes:

Instruction class	CPI
A	1
B	2
C	3

e.g ALU, Branch etc.

For a specific CPU design

- Two code sequences have the following instruction counts:

Program	Instruction counts for instruction class		
Code Sequence	A	B	C
1	2	1	2
2	4	1	1

- CPU cycles for sequence 1 = 2 x 1 + 1 x 2 + 2 x 3 = 10 cycles

  CPI for sequence 1 = clock cycles / instruction count

  = 10 /5 = 2

i.e average or effective CPI

- CPU cycles for sequence 2 = 4 x 1 + 1 x 2 + 1 x 3 = 9 cycles

  CPI for sequence 2 = 9 / 6 = 1.5

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

CPI = CPU Cycles / I

Instruction Frequency & CPI

- Given a program with *n* types or classes of instructions with the following characteristics:

i = 1, 2, …. n

C_i = Count of instructions of type$_i$ executed

CPI_i = Average cycles per instruction of type$_i$

F_i = Frequency or fraction of instruction type$_i$ executed

= C_i/ total executed instruction count = C_i/ I

Then:

Where: Executed Instruction Count I = ΣC_i

$$CPI = \sum_{i=1}^{n} (CPI_i \times F_i)$$

i.e average or effective CPI

Fraction of total execution time for instructions of type i = $\frac{CPI_i \times F_i}{CPI}$

T = I x CPI x C

Instruction Type Frequency & CPI

Program Profile or Executed Instructions Mix

$\frac{CPI_i \times F_i}{CPI}$

Base Machine (Reg / Reg)

Depends on CPU Design

Op	Freq, F_i	CPI_i	$CPI_i \times F_i$	% Time
ALU	50%	1	.5	23% = .5/2.2
Load	20%	5	1.0	45% = 1/2.2
Store	10%	3	.3	14% = .3/2.2
Branch	20%	2	.4	18% = .4/2.2
			Sum = 2.2	

Given

Typical Mix

$$CPI = \sum_{i=1}^{n} (CPI_i \times F_i)$$

i.e average or effective CPI

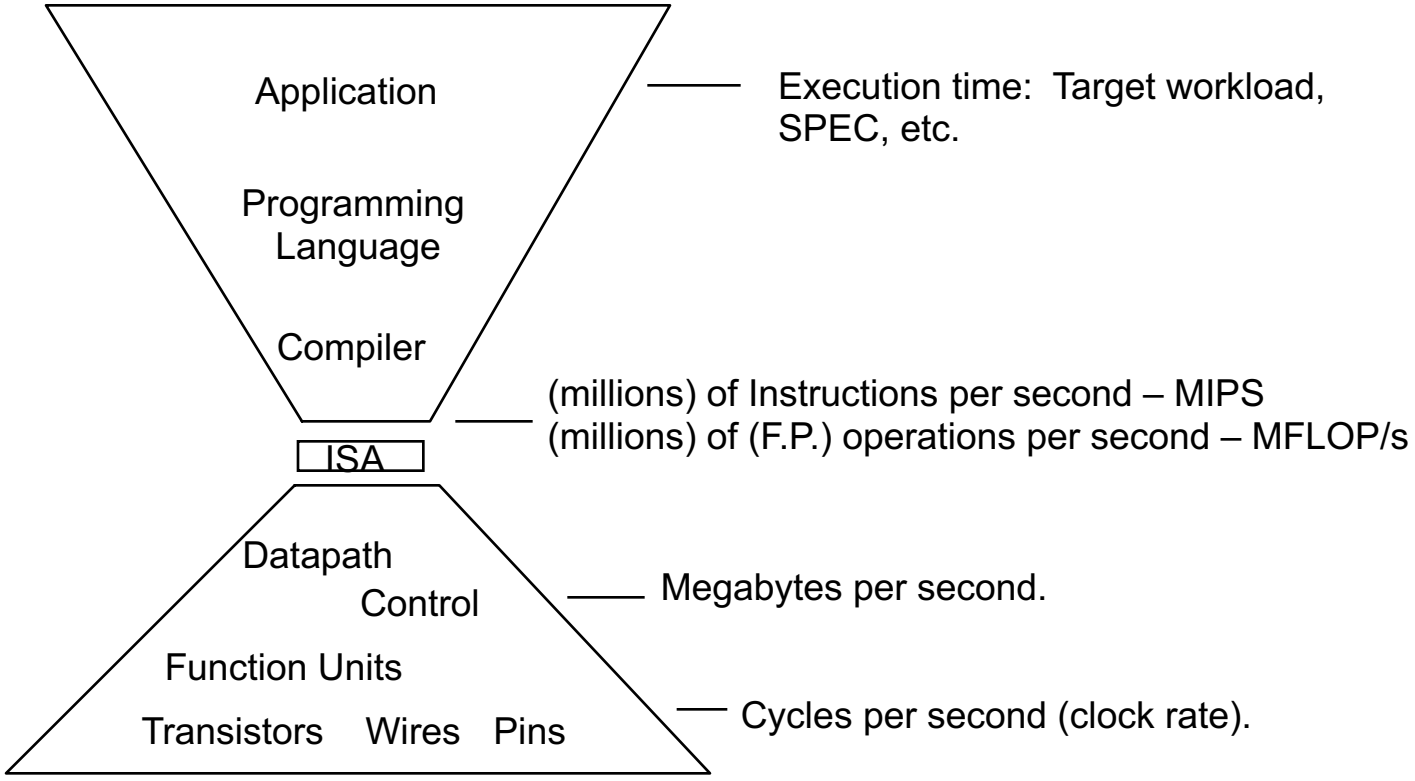
CPI = .5 x 1 + .2 x 5 + .1 x 3 + .2 x 2 = 2.2

= .5 + 1 + .3 + .4

T = I x CPI x C

Metrics of Computer Performance

(Measures)



Each metric has a purpose, and each can be misused.

Choosing Programs To Evaluate Performance

Levels of programs or benchmarks that could be used to evaluate performance:

- Actual Target Workload: Full applications that run on the target machine.
- Real Full Program-based Benchmarks:
  - Select a specific mix or suite of programs that are typical of targeted applications or workload (e.g SPEC95, SPEC CPU2000).
- Small "Kernel" Benchmarks: Also called synthetic benchmarks
  - Key computationally-intensive pieces extracted from real programs.
    - Examples: Matrix factorization, FFT, tree search, etc.
  - Best used to test specific aspects of the machine.
- Microbenchmarks:
  - Small, specially written programs to isolate a specific aspect of performance characteristics: Processing: integer, floating point, local memory, input/output, etc.

Types of Benchmarks

Pros		Cons
• Representative	Actual Target Workload	• Very specific. • Non-portable. • Complex: Difficult to run, or measure.
• Portable. • Widely used. • Measurements useful in reality.	Full Application Benchmarks	• Less representative than actual workload.
• Easy to run, early in the design cycle.	Small “Kernel” Benchmarks	• Easy to “fool” by designing hardware to run them well.
• Identify peak performance and potential bottlenecks.	Microbenchmarks	• Peak performance results may be a long way from real application performance

SPEC: System Performance Evaluation Corporation

The most popular and industry-standard set of CPU benchmarks.

Programs application domain: Engineering and scientific computation

- SPECmarks, 1989:
  - 10 programs yielding a single number ("SPECmarks").
- SPEC92, 1992:
  - SPECInt92 (6 integer programs) and SPECfp92 (14 floating point programs).
- SPEC95, 1995:
  - SPECint95 (8 integer programs):
    - go, m88ksim, gcc, compress, li, ijpeg, perl, vortex
  - SPECfp95 (10 floating-point intensive programs):
    - tomcatv, swim, su2cor, hydro2d, mgrid, applu, turb3d, apsi, fppp, wave5
  - Performance relative to a Sun SuperSpark I (50 MHz) which is given a score of SPECint95 = SPECfp95 = 1
- SPEC CPU2000, 1999:
  - CINT2000 (11 integer programs). CFP2000 (14 floating-point intensive programs)
  - Performance relative to a Sun Ultra5_10 (300 MHz) which is given a score of SPECint2000 = SPECfp2000 = 100
- SPEC CPU2006, 2006:
  - CINT2006 (12 integer programs). CFP2006 (17 floating-point intensive programs)
  - Performance relative to a Sun Ultra Enterprise 2 workstation with a 296-MHz UltraSPARC II processor which is given a score of SPECint2006 = SPECfp2006 = 1

All based on execution time and give speedup over a reference CPU

Example Problem

Op	Freq	Cycles	CPI(i)	Time
ALU	50%	1	0.5	23%
Load	20%	5	0.5	45%
Store	10%	3	0.3	14%
Branch	20%	2	0.4	18%

Average CPI: 2.2

- **How much faster would the machine be of reduce load time to 2 cycle?**
- **How does it compare with branch prediction to reduce 1 cycle off branch?**
- **What if 2 ALU instructions can be executed at once?**

Example Problem

- Compiler has to decide between two code sequences for a single machine. Based on the hardware implementation there are 3 classes of instructions A, B, C. They require 1, 2 and 3 cycles respectively.
- First code sequence has 5 instr. 2 of A, 1 of B, 2 of C.
- Second has 6 instr. 4 of A, 1 of B, 1 of C

- Which sequence is faster? By how much? What is CPI for each sequence?

Example Problem

- A given application written in Java runs in 15 sec on a machine. A new Java compiler requires only 0.6 as many instr. As old. Unfortunately it raises CPI by 1.1 times.
- How fast can we expect the application to run using this fast compiler?

Example Problem

- Two compilers are being tested for a 4 GHz machine with three different classes of instr. A, B, C requiring 1, 2, 3 cycles respectively. Both compilers are used to produce code for a large software.
- First compiler uses 5 billion Class A, 1 bn class B, and 1 bn Class C.
- Second uses 10 bn A, 1 bn B, 1 bn C.
- Which sequence is faster in mips?
- Which sequence faster according to exec. time?

Example Problem

- A 1 GHz processor takes 100 seconds to execute a program, while consuming 70 W of dynamic power and 30 W of leakage power. Does the program consume less energy in Turbo boost mode when the frequency is increased to 1.2 GHz?

Normal mode energy = 100 W x 100 s = 10,000 J
Turbo mode energy = (70 x 1.2 + 30) x 100/1.2 = 9,500 J

Note:
Frequency only impacts dynamic power, not leakage power.
We assume that the program's CPI is unchanged when frequency is changed, i.e., exec time varies linearly with cycle time.