Week 2

Performance Definitions

- Performance is in units of things-per-second
  - bigger is better
- If we are primarily concerned with response time
  - $\text{performance}(x) = \dfrac{1}{\text{execution\_time}(x)}$

- " X is n times faster than Y" means

$$n = \frac{\text{performance}(X)}{\text{performance}(Y)} = \frac{\text{execution\_time}(Y)}{\text{execution\_time}(X)}$$

- When is throughput more important than execution time?
- When is execution time more important than throughput?

Peformance Examples

- Time of Concorde vs. Boeing 747?
  - Concord is 1350 mph / 610 mph = 2.2 times faster
    = 6.5 hours / 3 hours
- Throughput of Concorde vs. Boeing 747 ?
  - Concord is 178,200 pmph / 286,700 pmph = 0.62 “times faster”
  - Boeing is 286,700 pmph / 178,200 pmph = 1.6 “times faster”
- Boeing is 1.6 times (“60%”) faster in terms of throughput
- Concord is 2.2 times (“120%”) faster in terms of flying time
- When discussing processor performance, we will focus primarily on execution time for a single job - why?

Understanding Performance

- How are the following likely to effect response time and throughput?
  - Increasing the clock speed of a given processor.
  - Increasing the number of jobs in a system (e.g., having a single computer service multiple users).
  - Increasing the number of processors in a sytem that uses multiple processors (e.g., a network of ATM machines).
- If a Pentium III runs a program in 8 seconds and a PowerPC runs the same program in 10 seconds, how many times faster is the Pentium?

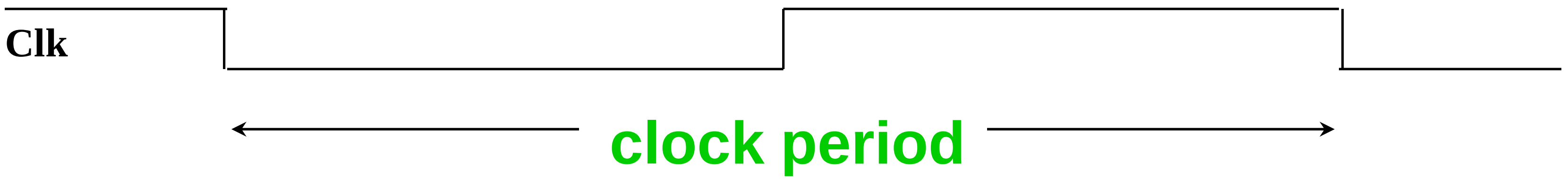
  n = 10 / 8 = 1.25 times faster (or 25% faster)
- Why might someone chose to buy the PowerPC in this case?

Definitions of Time

- Time can be defined in different ways, depending on what we are measuring:
  - Response time : Total time to complete a task, including time spent executing on the CPU, accessing disk and memory, waiting for I/O and other processes, and operating system overhead.
  - CPU execution time : Total time a CPU spends computing on a given task (excludes time for I/O or running other programs). This is also referred to as simply CPU time.
  - User CPU time : Total time CPU spends in the program
  - System CPU execution time : Total time operating systems spends executing tasks for the program.
- For example, a program may have a system CPU time of 22 sec., a user CPU time of 90 sec., a CPU execution time of 112 sec., and a response time of 162 sec..

Computer Clocks

- A computer clock runs at a constant rate and determines when events take placed in hardware.



- The clock cycle time is the amount of time for one clock period to elapse (e.g. 5 ns).
- The clock rate is the inverse of the clock cycle time.
- For example, if a computer has a clock cycle time of 5 ns, the clock rate is:

$$\frac{1}{5 \times 10^{-9} \text{sec}} = 200 \text{ MHz}$$

Computing CPU time

- The time to execute a given program can be computed as

  CPU time = CPU clock cycles x clock cycle time

  Since clock cycle time and clock rate are reciprocals

  CPU time = CPU clock cycles / clock rate

- The number of CPU clock cycles can be determined by

  CPU clock cycles = (instructions/program) x (clock cycles/instruction)

  = Instruction count x CPI

  which gives

  CPU time = Instruction count x CPI x clock cycle time

  CPU time = Instruction count x CPI / clock rate

- The units for this are

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

Example of Computing CPU time

- If a computer has a clock rate of 50 MHz, how long does it take to execute a program with 1,000 instructions, if the CPI for the program is 3.5?
- Using the equation

  CPU time = Instruction count x CPI / clock rate

  gives

  CPU time = 1000 x 3.5 / (50×10^{6}) = 70 μsec
- If a computer's clock rate increases from 200 MHz to 250 MHz and the other factors remain the same, how many times faster will the computer be?

$$\frac{\text{CPU time old}}{\text{CPU time new}} = \frac{\text{clock rate new}}{\text{clock rate old}} = \frac{250\text{ MHz}}{200\text{ MHZ}} = 1.25$$

- What simplifying assumptions did we make?

A program runs on computer A with a 2 GHz clock in 10 seconds. What clock rate must a computer B run at to run this program in 6 seconds? Unfortunately, to accomplish this, computer B will require 1.2 times as many clock cycles as computer A to run the program.

$$\text{CPU clock cycles}_A = 10 \text{ sec} \times 2 \times 10^9 \text{ cycles/sec}$$
$$= 20 \times 10^9 \text{ cycles}$$

$$\text{CPU time}_B = \frac{1.2 \times 20 \times 10^9 \text{ cycles}}{\text{clock rate}_B}$$

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

Computers A and B implement the same ISA. Computer A has a clock cycle time of 250 ps and an effective CPI of 2.0 for some program and computer B has a clock cycle time of 500 ps and an effective CPI of 1.2 for the same program. Which computer is faster and by how much?

Each computer executes the same number of instructions, I, so

$$\text{CPU time}_A = I \times 2.0 \times 250 \text{ ps} = 500 \times I \text{ ps}$$

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

Clearly, A is faster by the ratio of execution times

$$\frac{\text{performance}_A}{\text{performance}_B} = \frac{\text{execution\_time}_B}{\text{execution\_time}_A} = \frac{600 \times I \text{ ps}}{500 \times I \text{ ps}} = 1.2$$

Computing the overall effective CPI is done by looking at the different types of instructions and their individual cycle counts and averaging.
The overall effective CPI varies by instruction mix – is a measure of the dynamic frequency of instructions across one or many programs.

To look at an example, consider the following instruction mix:

Op	Freq	Cycles	CPI
ALU	50%	1	.5
Load	20%	5	1.0
Store	10%	3	.3
Branch	20%	2	.4
			2.2

How much faster would the machine be if a better data cache reduced the average load time to 2 cycles?

- Load à 20% x 2 cycles = .4
- Total CPI 2.2 –(1-0.4)= 1.6
- Relative performance is 2.2 / 1.6 = 1.38

How does this compare with reducing the branch instruction to 1 cycle?

  - Branch à 20% x 1 cycle = .2
  - Total CPI 2.2 –(0.4-0.2)=2.0
  - Relative performance is 2.2 / 2.0 = 1.1 We can now write the basic performance equation as:

$$\text{CPU time} = \text{Instruction\_count} \times \text{CPI} \times \text{clock\_cycle}$$

or

$$\text{CPU time} = \frac{\text{Instruction\_count} \times \text{CPI}}{\text{clock\_rate}}$$

$$\frac{\text{CPU time}}{\text{Program}} = \frac{\text{Instructions}}{\text{Program}} \times \frac{\text{ClockCycles}}{\text{Instruction}} \times \frac{\text{Seconds}}{\text{ClockCycle}}$$

$$\text{ExecutionTime} = \frac{1}{\text{Performance}} = (\text{Instr.Count}) \times (\text{CPI}) \times (\text{cycletime})$$

4. We want to compare the computers R1 and R2, which differ that R1 has the machine instructions for the floating-point operations, while R2 has not (FP operations are implemented in the software using several non-FP instructions). Both computers have a clock frequency of 400 MHz. In both we perform the same program, which has the following mixture of commands:

Type the command	Dynamic Share of instructions in program (p_i)	Instruction duration (Number of clock periods CPI_i)	
		R1	R2
FP addition	16%	6	20
FP multiplication	10%	8	32
FP division	8%	10	66
Non - FP instructions	66%	3	3

a) Calculate the MIPS for the computers R1 and R2.

b) Calculate the CPU program execution time on the computers R1 and R2, if there are 12000 instructions in the program?

c) At what mixture of instructions in the program will both computers R1 and R2 be equally fast?

Solution:

a) CPI = $\sum_{i=0}^{3} CPI_i * p_i$

Computer R1:

$$\text{CPI} = \sum_{i=1}^{3} CPI_i * p_i = 0{,}16 * 6 + 0{,}1 * 8 + 0{,}08 * 10 + 0{,}66 * 3 = 4{,}54$$

Computer R1 needs an average of 4.54 clock periods for one instruction

$$\text{MIPS} = \frac{f_{CPE}}{CPI * 10^6} = \frac{400 * 10^6}{4{,}54 * 10^6} = 88{,}1$$

Computer R1 executes an average of 88 100 000 instructions per second.

Computer R2:

$$\text{CPI} = \sum_{i=1}^{3} CPI_i * p_i = 0{,}16 * 20 + 0{,}1 * 32 + 0{,}08 * 66 + 0{,}66 * 3 = 13{,}66$$

Computer R2 needs an average of 13.66 clock periods for one instruction

$$\text{MIPS} = \frac{f_{CPE}}{\text{CPI} * 10^6} = \frac{400 * 10^6}{13{,}66 * 10^6} = 29{,}28$$

Computer R2 executes an average of 29 280 000 instructions per second.

b) $$\boldsymbol{CPU}_{\text{time}} = \frac{\text{Number\_of\_instructions}}{\boldsymbol{MIPS * 10^6}}$$

Another form of the equation to calculate the CPU time is:

$$CPU_{time} = Number\_of\_instructions * CPI * t_{CPU}$$

Computer R1:

$$\boldsymbol{CPU}_{\text{time}} = \frac{\text{Number\_of\_instructions}}{\boldsymbol{MIPS * 10^6}} = \frac{12000}{88{,}1 * 10^6} = 136{,}2 * 10^{-6} = 136{,}2\ \mu s$$

Computer R2:

$$\boldsymbol{CPU}_{\text{time}} = \frac{\text{Number\_of\_instructions}}{\boldsymbol{MIPS * 10^6}} = \frac{12000}{29{,}28 * 10^6} = 410 * 10^{-6} = 410\ \mu s$$

Our Goal

- Minimize time which is the product, NOT isolated terms
- Common error to miss terms while devising optimizations
  - E.g. ISA change to decrease instruction count
  - BUT leads to CPU organization which makes clock slower
- Bottom line: terms are inter-related

RISC vs. CISC

$T_{exec} = N * CPI * cycle\_time$

- RISCs (Reduced Instruction Set Computers) and CISCs (Complex Instruction Set Computers):
  - RISC CPUs try to reduce T_{exec} by:
    - reducing CPI
    - reducing HW complexity so that we can use faster clocks (shorter cycle times)
  - CISC CPUs try to reduce T_{exec} by:
    - reducing N (number of instructions executed)

RISC ISA

$$T_{exec} = N * CPI * cycle\_time$$

1. Load/Store Architecture
2. Instruction semantics are at low level
3. Small number of addressing modes
4. Uniform instruction format

1 & 2 : Fast operation

2 & 3 & 4 : Fetching and decoding of instructions is very quick

<u>Advantages:</u>

- HW is simple
- Logic delays are smaller => we can use faster clock

<u>Disadvantages:</u>

- Because of 2nd item => N goes up

Design Challenge:

- Growth in N should be compensated by the reduction in CPI and cycle time

CISC ISA

$$T_{exec} = N * CPI * cycle\_time$$

1. Many "operate" instructions with at least one memory operand
2. Instruction semantics are at high level
3. Many addressing modes
4. Non-uniform instruction format

1 & 2 : Slow operation

2 & 3 & 4 : decoding of instructions is very slow

<u>Advantages:</u>

- N is smaller

<u>Disadvantages:</u>

- Complex HW
- Larger logic delays => faster clock is not possible
- Higher CPI

Design Challenge:

- Growth in CPI and cycle time should be compensated by the reduction in N

Computing CPI

- The CPI is the average number of cycles per instruction.
- If for each instruction type, we know its frequency and number of cycles need to execute it, we can compute the overall CPI as follows:

$$CPI = \sum_{i=1} CPI_i \times F_i$$

- For example

Op	F_i	CPI_i	$CPI_i \times F_i$	% Time
ALU	50%	1	.5	23%
Load	20%	5	1.0	45%
Store	10%	3	.3	14%
Branch	20%	2	.4	18%
Total	100%		2.2	100%

Performance Summary

- The two main measure of performance are
  - execution time : time to do the task
  - throughput : number of tasks completed per unit time
- Performance and execution time are reciprocals. Increasing performance, decreases execution time.
- The time to execute a given program can be computed as:

  CPU time = Instruction count x CPI x clock cycle time

  CPU time = Instruction count x CPI / clock rate
- These factors are affected by compiler technology, the instruction set architecture, the machine organization, and the underlying technology.
- When trying to improve performance, look at what occurs frequently => make the common case fast.

Computer Benchmarks

- A benchmark is a program or set of programs used to evaluate computer performance.
- Benchmarks allow us to make performance comparisons based on execution times
- Benchmarks should
  - Be representative of the type of applications run on the computer
  - Not be overly dependent on one or two features of a computer
- Benchmarks can vary greatly in terms of their complexity and their usefulness.

Types of Benchmarks

Pros		Cons
• representative	Actual Target Workload	• very specific • non-portable • difficult to run, or measure • hard to identify cause
• portable • widely used • improvements useful in reality	Full Application Benchmarks (e.g., SPEC benchmarks)	•less representative
• easy to run, early in design cycle	Small “Kernel” Benchmarks	• does not measure memory system
• identify peak capability and potential bottlenecks	Microbenchmarks	• “peak” may be a long way from application performance

SPEC: System Performance Evaluation Cooperative

- The SPEC Bencmarks are the most widely used benchmarks for reporting workstation and PC performance.
- First Round SPEC CPU89
  - 10 programs yielding a single number
- Second Round SPEC CPU92
  - SPEC CINT92 (6 integer programs) and SPEC CFP92 (14 floating point programs)
  - Compiler flags can be set differently for different programs
- Third Round SPEC CPU95
  - New set of programs: SPEC CINT95 (8 integer programs) and SPEC CFP95 (10 floating point)
  - Single compiler flag setting for all programs
- Fourth Round SPEC CPU2000
  - New set of programs: SPEC CINT2000 (12 integer programs) and SPEC CFP2000 (14 floating point)
  - Single compiler flag setting for all programs
- Value reported is the SPEC ratio
  - CPU time of reference machine / CPU time of measured machine

Other SPEC Benchmarks

- JVM98:
  - Measures performance of Java Virtual Machines
- SFS97:
  - Measures performance of network file server (NFS) protocols
- Web99:
  - Measures performance of World Wide Web applications
- HPC96:
  - Measures performance of large, industrial applications
- APC, MEDIA, OPC
  - Meausre performance of graphics applications
- For more information about the SPEC benchmarks see: http://www.spec.org.

Examples of SPEC95 Benchmarks

- SPEC ratios are shown for the Pentium and the Pentium Pro (Pentium+) processors

Clock Rate	Pentium SPECint	Pentium+ SPECint	Pentium SPECfp	Pentium+ SPECfp
100 MHz	3.2	N/A	2.6	N/A
150 MHZ	4.4	6.0	3.0	5.1
200 MHZ	5.5	8.0	3.8	6.8

- **What can we learn from this information?**

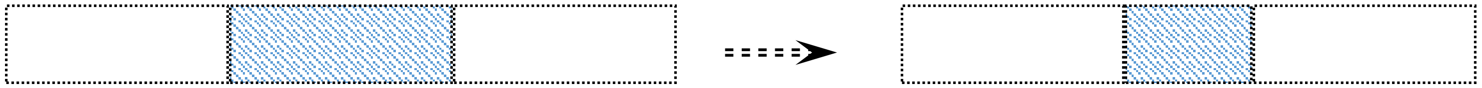
Poor Performance Metrics

- Marketing metrics for computer performance included MIPS and MFLOPS
- MIPS : millions of instructions per second
  - MIPS = instruction count / (execution time x 10^6)
  - For example, a program that executes 3 million instructions in 2 seconds has a MIPS rating of 1.5
  - Advantage : Easy to understand and measure
  - Disadvantages : May not reflect actual performance, since simple instructions do better.
- MFLOPS : millions of floating point operations per second
  - MFLOPS = floating point operations / (execution time x 10^6)
  - For example, a program that executes 4 million instructions in 5 seconds has a MFLOPS rating of 0.8
  - Advantage : Easy to understand and measure
  - Disadvantages : Same as MIPS,only measures floating point

Amdahl's Law

Speedup due to an enhancement is defined as:

$$\text{Speedup} = \frac{\text{ExTime old}}{\text{ExTime new}} = \frac{\text{Performance new}}{\text{Performance old}}$$



Suppose that an enhancement accelerates a fraction $\text{Fraction}_{\text{enhanced}}$ of the task by a factor $\text{Speedup}_{\text{enhanced}}$,

$$\text{ExTime}_{\text{new}} = \text{ExTime}_{\text{old}} \times \left[(1 - \text{Fraction}_{\text{enhanced}}) + \frac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}} \right]$$

$$\text{Speedup} = \frac{\text{ExTime}_{\text{old}}}{\text{ExTime}_{\text{new}}} = \frac{1}{(1 - \text{Fraction}_{\text{enhanced}}) + \frac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}}}$$

Example of Amdahl's Law

- Floating point instructions are improved to run twice as fast, but only 10% of the time was spent on these instructions originally. How much faster is the new machine?

$$\text{Speedup} = \frac{\text{ExTime}_{\text{old}}}{\text{ExTime}_{\text{new}}} = \frac{1}{(1 - \text{Fraction}_{\text{enhanced}}) + \dfrac{\text{Fraction}_{\text{enhanced}}}{\text{Speedup}_{\text{enhanced}}}}$$

$$\text{Speedup} = \frac{1}{(1 - 0.1) + 0.1/2} = 1.053$$

- **The new machine is 1.053 times as fast, or 5.3% faster.**
- **How much faster would the new machine be if floating point instructions become 100 times faster?**

$$\text{Speedup} = \frac{1}{(1 - 0.1) + 0.1/100} = 1.109$$

Estimating Perfomance Improvements

- Assume a processor currently requires 10 seconds to execute a program and processor performance improves by 50 percent per year.
- By what factor does processor performance improve in 5 years?

  $(1 + 0.5)^5 = 7.59$

- How long will it take a processor to execute the program after 5 years?

  $ExTime_{new} = 10/7.59 = 1.32$ seconds

- What assumptions are made in the above problem?

Performance Example

- Computers M1 and M2 are two implementations of the same instruction set.
- M1 has a clock rate of 50 MHz and M2 has a clock rate of 75 MHz.
- M1 has a CPI of 2.8 and M2 has a CPI of 3.2 for a given program.
- How many times faster is M2 than M1 for this program?

$$\frac{\mathbf{ExTime_{M1}}}{\mathbf{ExTime_{M2}}} = \frac{\mathbf{IC_{M1} \times CPI_{M1} / Clock\ Rate_{M1}}}{\mathbf{IC_{M2} \times CPI_{M2} / Clock\ Rate_{M2}}} = \frac{\mathbf{2.8/50}}{\mathbf{3.2/75}} = \mathbf{1.31}$$

- What would the clock rate of M1 have to be for them to have the same execution time?

Summary of Performance Evaluation

- Good benchmarks, such as the SPEC benchmarks, can provide an accurate method for evaluating and comparing computer performance.
- MIPS and MFLOPS are easy to use, but inaccurate indicators of performance.
- Amdahl’s law provides an efficient method for determining speedup due to an enhancement.
- Make the common case fast!